Systems modelling approach to drought management strategies in the Lake Kariba district of Zambia

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SYSTEMS MODELLING APPROACH TO DROUGHT MANAGEMENT STRATEGIES IN THE LAKE KARIBA DISTRICT OF ZAMBIA

by

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A Thesis submitted in partial fulfilment for the degree of Doctor of Philosophy at the University of Wollongong, N.S.W. 2500.

February, 1990

To

my deceased father and mother; and

to my wife and children

TABLE OF CONTENTS

ABSTRACT OF SYSTEMS MODELLING APPROACH TO DROUGHT MANAGEMENT STRATEGIES IN THE LAKE KARIBA DISTRICT OF ZAMBIA

The frequent occurrences of drought in the Lake Kariba District has been accompanied by declining agricultural productivity. This in turn has resulted in low income, famine, starvation, malnutrition, poor health and poverty among the people in the lake Kariba District. the central objective of this thesis is, therefore, to derive a set of agricultural management strategies that would minimize these adverse effects of drought. The pursuit of this objective involved the following:

(a) formulation of decision frameworks for the "with irrigation" and the "without irrigation" strategies;

(b) empirical demonstration of the applicability of these frameworks to the Lake Kariba District;

(c) illustration of management strategies that are pertinent to the district; and

(d) analysis of the trade-offs that possibly exist between the goals of income maximization and food stability.

Objectives (a), (b) and (c) were analyzed by developing two sets of frameworks, namely a deterministic framework for the "with irrigation" option, and stochastic frameworks for the "with irrigation" and the "without irrigation" options. In the deterministic framework, risks and uncertainty are assumed to be non-existent, despite the stochastic nature of rainfall in the area. This assumption is justified on the strength that water for irrigation is from Lake Kariba. However, the certainty assumption is unrealistic given the fact that the Lake Kariba District is prone to drought. Hence, the introduction of risk and uncertainty into the stochastic framework enables a closer

resemblance to reality. Hence, the evaluation of decision strategies was based on the results of the stochastic frameworks.

Results of the application of the frameworks indicate that the "with irrigation" option is more superior to the "without irrigation" option, in terms of income. Further, the results prescribe a diversified cropping pattern which is a pattern that is favoured by decision makers. The "with irrigation" option generates a significantly higher income than the "without irrigation" option due to the feasibility of undertaking cropping practices during both wet an dry seasons.

A survey of the study area also revealed that the community is concerned with objectives other than maximizing income. Of these other objectives, "food stability" is a dominant objective. Hence, this thesis also involved an analysis of the trade-offs that prevail between the maximization of income from growing cash crops and maximization of food stability from producing food crops. This trade-off analysis was set in the context of the "with irrigation" option.

AUTHOR'S CERTIFICATION

I certify that the substance of this thesis has not already been submitted for any degree and is not being currently submitted for any other degree.

I certify that any help received in preparing this thesis, and all sources used have been acknowledged in this thesis.

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ACKNOWLEDGEMENTS

First and foremost I am grateful to my supervisor, Dr. Dodo J. Thampapillai for his guidance, encouragement and generous allocation of time towards the development and completion of this thesis. I do greatly appreciate his supervisory skills.

Professor Claus Hanf offered very helpful suggestions on the incorporation of risk into the frameworks that have been developed. In fact he is the one who has developed my interest in risk modelling.

I am also grateful to Dr. Dennis O'Brien for his valuable suggestions and comments during the early stages of the development of the frameworks of this thesis. His suggestions on the stochastic framework is most valuable and very much appreciated.

I am grateful to the Australian Development Assistance Bureau (AIDAB) for providing me a generous scholarship. The patience and willingness of AIDAB to extend my scholarship from four years to five years is greatly appreciated.

I thank The University of Zambia for granting me study leave and for the encouragement which was accorded me. Similarly I thank Dr. Charles Harvie, Mr. Heikki Nivala and his wife, Patricia, for giving me encouragement during times when I felt depressed in writing my thesis.

I am grateful to Dr. John Kennedy, Associate Professor Brian Hardaker, Dr. Ernest Baafi, Dr. Kwabena Anaman, Professor T. Scudder, Mrs Elizabeth Bradlow and Mrs Mary Liverini for constructive suggestions and valuable help.

The information and various documents on the pattern of rainfall, Lake Kariba water levels, maps and others provided by the

Central African Power Corporation (CAPCO), Departments of Meteorology in Zimbabwe and Zambia and other governments departments in both countries is very much appreciated.

I wish to thank Mrs Julie Chin for patiently typing this thesis; Di Kelly and Stephen Allen for diligently proof reading my thesis and Mr. Richard Miller for drawing the figures.

Staff in the Economics Department had been very helpful. Professor Dudley Jackson, Wolfgang Brodesser and Sophie Abercrombie stand out. Wolfgang spent long hours explaining to me about various computer programmes.

Lastly, but not least, I am extremely grateful to my wife Patricia and children: Moses, Masautso, Masiye and Mukena.

All residual errors or omissions are the sole responsibility of the author.

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

1.1 The Nature of the Drought Problem and the Objectives of this Study.

The occurrence of drought is a common feature in the Lake Kariba District, which is sometimes known as the Gwembe Valley. During the past seventy years, drought events have occurred at least thirty times. These drought events have been invariably accompanied by famine (Scudder 1962, 1985; Watts, 1984 and Banda, 1985). Not surprisingly, starvation, malnutrition, poor health and poverty are widespread in the area. For example, the annual calorie intake in the Lake Kariba area is estimated to be 1500 calories per head and this is well below the level recommended by the World Health Organisation. Per capita annual income is a meagre 66 kwacha per head (Zambia Nutrition Commission, 1986) which when converted to Australian currency is $22 per head. Whilst detailed statistical evidence is not readily available at the district level, life expectancy is low and the rate of child mortality is high. The central objective of this thesis is the derivation of agricultural management strategies that would minimize such adverse effects of drought.

Scudder (1985) describes in detail the management strategies that have been adopted to counter the adverse effects of drought. Of these the prominent agricultural strategies are:

(a) soil conservation measures,

(b) cropping pattern, and

(c) irrigation.

A brief discussion of each of these strategies follows.

Soil Conservation Measures

Soil conservation measures which have been adopted in the past included: (a) contour ridging, (b) mulching, (c) destocking of livestock, (d) planting of trees, and (e) conservation of forests. However, these measures had limited success despite the heavy fines and punishments imposed on those people who failed to adopt them. The lack of success of these measures may be attributed to several causes. These include: the ad hoc manner in which soil conservation measures were administered (Scudder, 1985 and Banda, 1985) and the attitudes of farmers to liken certain soil conservation measures (such as destocking of livestock) to measures that cause loss of output and income. Further, during the colonial period, the Zambians also viewed the soil conservation measures as an imposition by the ruling British. Hence, the non compliance of drought management strategies was mistakenly associated with a demonstration of resilience.

Cropping Pattern

Cropping pattern involved introducing a variety of high yielding cash crops such as cotton, sunflower, groundnuts and tobacco. The reason for this was to exchange the revenue earned from cash crops with food imported from other regions (Scudder, 1962; Mulfrod, 1967 and Banda,1985). However, this strategy also failed, because it did not adequately accommodate other pertinent measures such as: timely application of fertilizer and the adequate use of other agricultural inputs (Arnon, 1987 and Gakou, 1987). The chief constraint to the adoption of these measures was the spiralling of energy prices which rendered many agricultural inputs expensive.

However, the major resistance to changing cropping patterns has been conflicting beliefs among the members of the community of the

Lake Kariba District. As indicated, some believe that the resources of the district should be allocated to cash crops, and that such allocation would provide adequate income to purchase food from elsewhere. Alternatively, others believe that a stable supply of food can be maintained only by committing the resources of the district to food crops. Further, the issue concerning cropping patterns is also a manifestation of the conflicts between two social objectives that are pursued by the community, namely maximizing income by growing cash crops and maintaining a stable supply of food by growing food crops.

Irrigation

Several feasibility studies (Roberts, 1961; Honisch and Hailey, 1971; World Bank, 1983; AGRINDCO, 1984, 1987 and the Gwembe Valley Company, 1987) have all recommended irrigating several crops using furrow or sprinkle irrigation methods. Furrow irrigation was started in four areas within the Lake Kariba District. These are: Siatwinda, Mkandabwe, Buleya Malima and Chirundu. However, these irrigation projects too have failed. Banda (1985) provides some reasons for their failure. These are:

(a) lack of government funds to maintain and operate the irrigation scheme,

(b) poor irrigation lay-out and inadequate management,

(c) lack of facilities to educate the people in the area about water management and appreciation about the irrigation project itself; and

(d) lack of procedures to tie project planning to the needs and resources of the district.

Furthermore, the decision making environment of the Lake Kariba District is one which is subject to risk and uncertainty. The chief cause of risk and uncertainty is of course the variability in levels of rainfall and the unanticipated occurrence of drought. Several authors such as Anderson, Dillon and Hardaker (1977) and Hazell and Norton (1986) have indicated that management strategies which ignore the role of risk are likely to fail. A review of past decisions in the Lake Kariba District reveals that a study of risk has been virtually absent. Hence, the failure of the irrigation strategies in the district can be also attributed to the lack of consideration given to risk. According to Watts (1984), drought control strategies have also failed in the study area because they did not account for efficient utilization of resources in the district.

Following the failure of these irrigation schemes, there is divided opinion among government policy makers regarding the choice of a strategy for drought management. Some favour the adoption of irrigation with proper management as a strategy for alleviating famines and other adverse effects that are caused by drought in the Lake Kariba District. Others argue against irrigation and concentrate on the choice of appropriate cropping patterns which include drought resistant crops. Those who argue against irrigation (Banda, 1985 and Scudder, 1985) point out that irrigation is too costly to construct and operate and that it would lower the water levels in Lake Kariba. Several other scientists (Vermeer, 1981; Arnon, 1987; Gokou, 1987 and World Commission on Environment and Development, 1987) have also argued against embarking on large-scale irrigation projects in Africa. The arguments they raise against irrigation include the following.

(a) African countries do not have sufficent capital for investment in irrigation projects. The lack of capital also constrains the efficient maintenance of irrigation projects.

(b) Irrigation projects are biased towards growing cash crops (cotton and sunflower, groundnuts and tobacco) instead of basic food crops that are consumed by farm families. This is because investors want to quickly recoup their investments. Thus irrigation through its emphasis on cash cropping has intensified the problems of famine and starvation instead of solving them. This is especially the case when irrigation schemes are not properly managed.

(c) Irrigation projects also cause environmental problems. Some of these are: soil salinity, water logging which in turn cause soil leaching and the possible spread of diseases such as malaria.

Those who argue for irrigation (World Bank,1983; the Gwembe Valley Company Report,1987; AGRINDCO,1987) in the Lake Kariba District do so on the basis of the high yields that it brings to various crops. They point out that heavy capital operation and maintenance costs demanded by irrigation would be offset by the profits that are realized from high crop yields due to irrigation.

The Zambian policy makers are hence confronted with a decision problem because both the "for" and "against" irrigation arguments seem to be convincing. Thus, it appears that for the time being the decision makers have decided to encourage rainfed cropping patterns in the district, until the decision problem concerning irrigation is resolved. The consensus in the literature (Garbrecht and Askoy, 1969; Honisch and Hailey, 1971 and the Gwembe District Agricultural Department, 1984 and 1986) is that such a decision problem can be resolved by evaluating the relative desirability of two broad types of strategies, namely, "with irrigation" and the "without irrigation".

Such evaluations would entail a consideration of the resource endowments of the Lake Kariba District and the efficient allocation of these resources within the context of each type of strategy. This is particularly relevant, given that inefficient allocation of resources has been often cited as a cause for exacerbating the effects of drought, (Watt, 1984). Further, following (Hazell and Norton, 1986) the evaluation of the two types of strategies should also recognize the effects of risk and uncertainty in drought management. As illustrated subsequently in chapter 2, these evaluations are best done through the development of mathematical programming models. However, mathematical programming models have not been developed and applied for the Lake Kariba District. Hence, the development of such models is important as well as useful. Thus, in this study, mathematical programming models have been chosen as the appropriate components of the decision frameworks that have to be developed.

As indicated previously, the central objective of this thesis is to derive a set of agricultural management strategies that would minimize the adverse effects of drought. The pursuit of this objective involves the following:

(a) formulation of decision frameworks for the "with irrigation" and the "without irrigation" strategies;

(b) empirical demonstration of the applicability of these frameworks to the Lake Kariba District; and

(c) illustration of management strategies that are pertinent to the district.

Given that the community of the Lake Kariba District is surrounded by risk and uncertainty in terms of rainfall and drought events, it is pertinent to incorporate the risks that are taken by farmers into the frameworks that are to be formulated. It is also pertinent, given the concerns of inefficient resource use, that the frameworks are capable of generating strategies that permit efficient resource use. Besides, since cash cropping at the expense of food crops has dominated monetary goals in terms of recouping investments that are made in irrigation, a further objective is also to analyze the trade-offs that possibly exist between the goals of income maximization and food stability.

1.2 Outline of this Thesis

This thesis proceeds along the following lines. In chapter 2, a discussion of the definitions of drought is presented, and the various drought management strategies and decision frameworks are reviewed. Also in chapter 2 is a discussion of the need to formulate decision frameworks which overcome some of the inadequacies of existing frameworks.

Chapter 3, describes the study area and gives an overview of the decision frameworks that are to be applied in this study. This overview illustrates the models that constitute the framework and the linkages between the decision models and resource endowments in the Lake Kariba District. Two categories of frameworks are distinguished in chapter 3, namely those representing deterministic and stochastic decision frameworks. The specification and empirical estimation of the deterministic and stochastic frameworks that were illustrated in chapter 3 are performed in chapter 4. These frameworks are applied in the context of the two alternative strategies, namely the "with irrigation" and the "without irrigation".

The results of the application of the frameworks, and the comparison between the two types of strategies are reported in Chapter 5. The comparison reveals that the "with irrigation" strategy is superior. The framework that generates the preferred strategy is then adapted in Chapter 6 to examine the trade-offs between the objectives of income maximization and food stability.

Chapter 6 illustrates, through a multiple objective programming method, that the twin objectives of maximizing income from cash crops and maintaining a stable supply of food from food crops are in conflict. Hence, a weighting method is used to generate a trade-off function which could assist the decision maker in choosing an appropriate management strategy.

Chapter 7, is a summary of the research and implications for further research in the Lake Kariba District. For ease of reading, detailed statistical material, tables, etc. are placed in appropriate appendixes at the end of the thesis.

CHAPTER 2 A BRIEF REVIEW OF THE LITERATURE

The aim of this thesis as indicated in Chapter 1 is to derive a set of strategies for drought management, through the development and application of decision frameworks that: recognize the role of drought event uncertainties, and permit the efficient allocation of resources in the Lake Kariba District. However, the development of frameworks requires an understanding of the definition and causes of drought. Hence, in Section 2.1, the various definitions of drought are reviewed and this is followed by a review of the causes of drought in Section 2.2. The various decision models that have been formulated and applied in the context of drought and related management problem are considered in Section 2.3.

Previous studies on the Lake Kariba District (World Bank 1983, Department of Agriculture 1984, and AGRINDCO 1987) have all indicated that the choice of an optimum strategy is best guided by a consideration of all resource endowments in the Lake Kariba District. Further, given that mathematical programming models are capable of evaluating all possible patterns of resource allocation (Thomas and Revelle, 1966; Vedula and Rogers, 1981; Hazell and Norton, 1986) the models that constitute the decision frameworks of this study would belong to the category of mathematical programming models. Hence, the review in Section 2.3 is confined to the various frameworks that employ mathematical programming.

The final section of this chapter deals with the implications of the reviews for this thesis.

2.1 Definition of drought

A number of scientists such as Whipple (1966), Dury (1983) and Glantz (1987) have argued that drought acquires as many definitions as the disciplines studying it. They further explain that the definitions of drought not only differs among disciplines but also among analysts within the same discipline. Herein the definitions offered by hydrologists, agriculturists and meteorologists are considered.

2.1.1 Hydrological drought

Hydrological drought as defined by Dracup, Lee and Paulson (1980) is a situation where the water level in a stream, river, lake or reservoir falls below a pre-determined level. This level usually represents the mean average of a set of historical data on water levels. According to them a drought situation has three attributes, namely (a) duration, (b) severity, and (c) magnitude.

They describe the duration of drought as the consecutive years for which the annual water level is below the long-term mean. The severity of drought is described as the cumulative deficit of water level for that duration, whilst the magnitude of drought refers to the deficit of water level for that duration. Magnitude is also interpreted as severity divided by duration. Guven (1983) and Lee, Sadeghipour and Dracup (1986) define hydrological drought in terms of duration, deficit sum and truncation level or mean average of time series water level data. Guven (1983) illustrates hydrological drought diagrammatically as in Figure 2.1. In this Figure, X_i represents the water level in time period i, and X_0 is mean or truncation level of water level data. For Guven, any year when water level is below X_0 indicates a drought year. L in Figure 2.1 represents the duration of drought in a given period. For example, L = 2 indicates a drought duration of 2 time periods. DL in Figure 2.1 indicates the deficit sum or the severity of drought in a given period.

2.1.2 Meteorological drought

Meteorological drought is defined by Glantz (1987) as a dry period caused by a shortage of rainfall, which in turn causes soil moisture stresses for plants and insufficient water levels in streams. According to him the degree of dryness differs from place to place and is dependent on the "use value" of water in a particular situation. He further explains that meteorological drought in Africa is not easily identifiable due to the paucity of meteorological and climatological data in many parts of the African Continent. The definition of drought in terms of insufficient rainfall has been widespread, as for example, illustrated by Singh (1978) and Winstanley (1976). Yet such definitions are restrictive and as Yevjevich (1967) indicates, these definitions need to be extended to include factors such as evaporation, run-off, and soil moisture levels.

2.1.3 Agricultural drought

Agricultural drought is usually defined as the state of insufficient soil moisture to sustain plant growth through the various stages of development, (Glantz, 1987). Further, it is not only the gross amount of soil moisture per se which is of critical importance, but also the relative availability of this soil moisture at each stage of plant growth.

As Moore (1961) explains, the relationship between soil moisture and plant growth is important in the consideration of agricultural drought. Moore (1961) considers three types of linear relationships. The first is an assumed positive relationship between

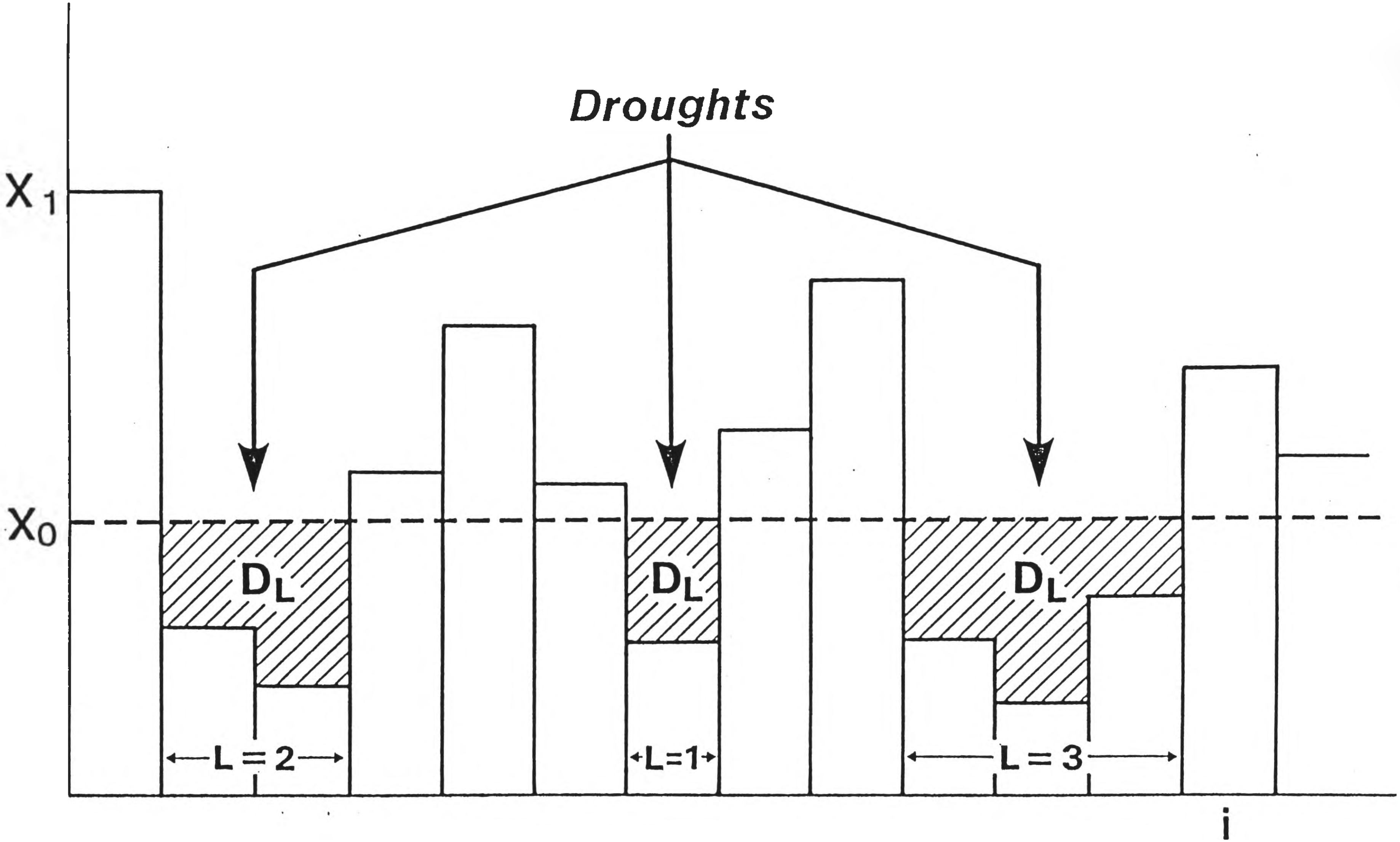

Figure 2.1 Hydrological definition of drought

Source: D. Guven, (1983)

plant growth and soil moisture. In the second, the relationship between plant growth and soil moisture is considered in the context of the wilting point of soil moisture level. The reduction in plant growth is regarded as insignificant if soil moisture levels do not reduce to wilting point. The third relationship includes other variables such as:

(a) soil moisture stress,

(b) soil type; and

(c) plant characteristics

The linearity assumption in the relationship between plant growth and soil moisture has been questioned by others. For example Gardner (1960), illustrates a non-linear relationship. There have also been some variants of the definitions of drought which employ the soil moisture-plant growth relationships. For example Dale and Shaw (1965) define a drought day as one in which the soil moisture in a plant's root zone is insufficient for normal plant development.

Other studies which consider drought in terms of the relationship between soil moisture levels and plant development are: Barger and Tom (1949), Tanner (1957), Knetsch (1959), Parks and Knetsch (1959), and Denmead and Shaw (1962). The definition of drought has also been extended to include the relationship between soil moisture and crop yields. A study by Hall and Butcher (1968) illustrates that reductions in crop yield occur due to shortage of water in the soil during certain stages of plant growth. However, Classen and Shaw (1970) show that crop yield reductions are more significant if soil moisture stress occurs during plant's tasselling stage. O'Brien (1981) uses experimental data on soil moisture to estimate yield reductions of rice in the Cale Region of the Phillipines. Some of the other studies which have analyzed drought in relation to crop yields and soil moisture stress are: Steward and Hagan (1970), Flinn (1976)

Jackson (1977) Aboitiz, Labadie and Heermann (1986), Gouuevsky and Maidment (1984), Marti, Watts and Gilley (1984) and Charnock (1986).

Drought has also been defined in terms of evapotranspiration or consumptive use (Hargreaves, 1956; Goodrich, 1956; Israelsen and Hansen, 1962 and Hargreaves, 1968). Further, evapotranspiration represents a convenient means of defining crop water requirements (Israelsen and Handen, 1962). Hence a drought is defined as the situation when rainfall or soil moisture levels are insufficient to meet the evapotranspiration needs of a plant. A potential drought situation can also be explained in terms of the variables that influence evapotranspiration namely, temperature, duration of plant growth, precipitation, stage of plant development and cropping practices. For example given that evapotranspiration rates are high during periods of high temperature, a drought is likely to occur if such periods are accompanied by low rainfall and/or lack of access to other sources of water such as irrigation. Hargreaves (1956) has computed evapotranspiration for various crops in the United States, and further argues that these computed values may be applicable to similar crops grown in other parts of the world under similar climatic and agronomic conditions. The use of computed evapotranspiration appears to be widespread in many developing countries where experimental data on crop yield-soil moisture relationship is lacking (Muchindu, 1986). Evapotranspiration data for various crops have been computed in Zambia by the Nanga National Irrigation Scheme, (Nanga Irrigation, 1985). Hence, given this availability of evapotranspiration data, this study defines drought in terms of evapotranspiration. That is, drought prevails whenever soil moisture levels are insufficient to meet crop water requirements which are measured in terms of evapotranspiration. However, as will be illustrated subsequently the various definitions of drought are also introduced in the decision frameworks.

2.2 Causes of drought

Causes of drought are many and varied. Following several in-depth studies on drought, for example, Yevjevich (1967), Singh (1978), Vermeer (1981), Dury (1983), Barrow (1987) and Glantz (1987) the causes of drought can be grouped into two broad categories, namely:

(i) physical or natural causes of drought; and

(ii) human causes of drought.

These two categories of drought are discussed below.

2.2.1 Physical or natural factors that cause drought

Although the distinction between physical and human causes of drought can be elusive (Wallen, 1966), the distinction is retained herein for purposes of clarity and simplicity. Following Wallen (1966), the natural causes of drought can be classified into causes that are associated with the earth's atmosphere, topography and weathering. The detailed classification is illustrated in Figure 2.2.

Wallen (1966) indicates that topography may cause drought in two ways. Distance from the ocean might make it very difficult for the moisture carried by oceanic winds to reach inland countries, thus rendering them prone to occurrences of drought. Further, high mountain ranges can also prevent these moisture carrying winds from reaching certain places, thus causing drought in these places.

Weathering can be caused by chemical or mechanical factors, which result in soil erosion. The loss of the surface layers of soils can

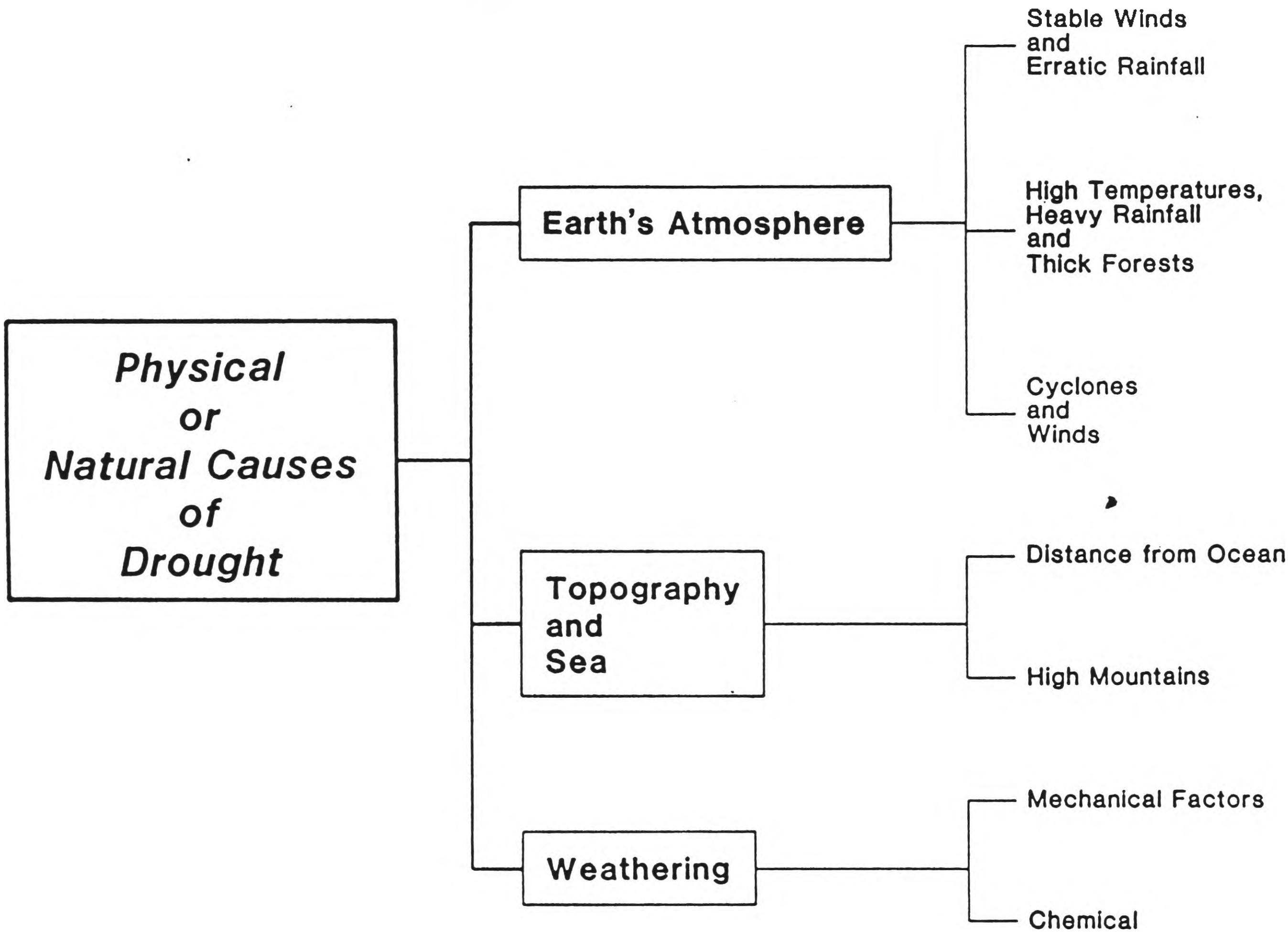

Figure 2.2 Physical or natural causes of drought

lead to drought due to reductions in moisture holding capacity. Bennette (1955) considers that soil erosion is caused by heavy rainfall and strong winds. That is, for example, heavy rainfall during a given period can lead to drought in subsequent periods. This is due to soil moisture stress in subsequent periods caused by the loss of the surface layers of soils during heavy rainfall.

Barrow (1987) considers the natural factors which cause drought in three regions of the tropics as follows.

(i) In the wet equatorial tropics which occupy 10° to the North and South of the equator, rainfall is intense, resulting in dense forests.

(ii) The sub-humid or wet dry tropics have two distinct seasons, namely dry and wet season. The wet season is characterized by green vegetation and the soil is generally well covered with shrubs and other plants. Thus, soil moisture is usually well retained because of negligible soil erosion during this season. However, the dry season can prompt soil moisture stress because of soil degradation which occurs due to the burning of fire and overgrazing.

(iii) In the tropical drylands or savannas, which lie between 23° North and 35° South of the equator, rainfall is generally erratic. Some years of heavy rainfall are followed by years of poor rainfall. This part of the tropics also has a larger concentration of livestock which sometimes results in overgrazing and a general deterioration of the environment.

2.2.2 Human causes of drought

Human causes of drought are insidious suchthat their effects are only felt after extended periods of time. Moreover, the interrelationship between human and natural causes of drought makes it extremely difficult to discuss one without discussing the other. However, for reasons of simplicity, the human causes of drought are summarized in Figure 2.3 below, and are classified into the following categories:

(i) deforestation caused by the expansion of population;

(ii) intensive agriculture involving: excessive fertilizer and pesticide application; construction of huge state farms, irrigation projects and poor farm management;

(iii) government policies, especially those that are intended for enhanced production but unintentionally prompt soil degradation and thus drought; and

(iv) pollution and toxic wastes from improper methods of industrial waste disposal.

Vermeer (1981) while recognizing natural causes of drought in the Sahelian countries considers human causes as well. According to him, migration of people from rural to urban areas in search of work, deprives the rural sector of labour and makes the already over crowded urban areas more crowded. The expansion of urban areas generates demand for more food and more firewood to burn charcoal. A majority of the people in African urban townships depend on firewood as a source of energy. This increasing demand for fuelwood has thus prompted deforestation. He also outlines an increase in human population as having resulted in deforestation and overgrazing in some parts of Africa. Deforestation in turn causes soil degradation and

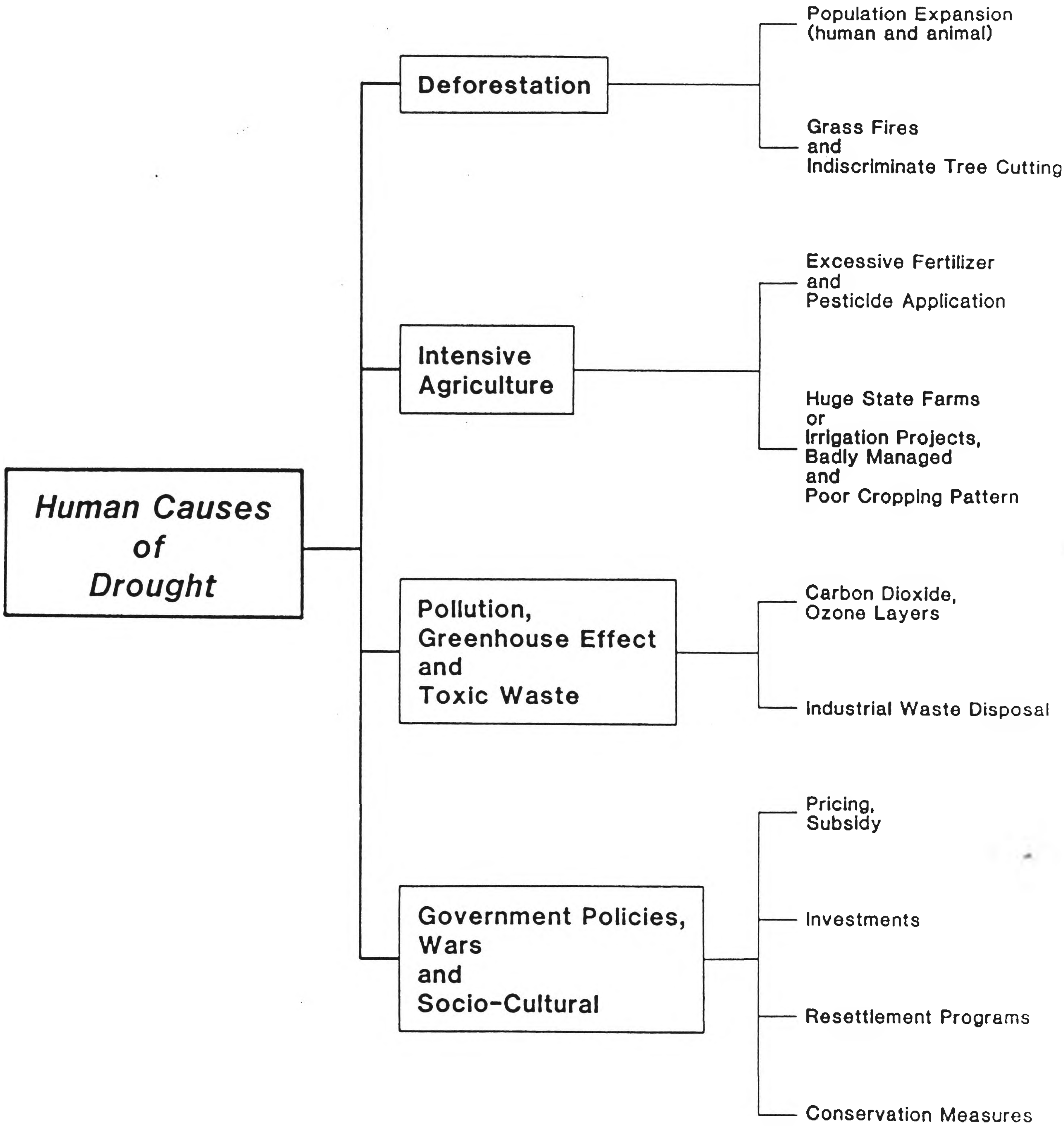

Figure 2.3 Categories of human causes of drought

expand desertification, especially in countries on the fringes of the Sahara and Kalahari deserts.

Barrow (1987) and Glantz (1987) consider various government policies that have contributed to the drought problems of certain African countries. Some of these policies are as follows:

(i) agricultural policies that promote cash cropping at the expense of food crops,

(ii) government policies which allocate more investible funds to large state farms and neglect farms based on small-scale holder schemes,

(iii) government policies of subsidizing agricultural inputs such as fertilizer, chemicals and pesticides encouraging farmers to apply more of these inputs and thus accelerating soil degradation; and

(iv) the resettlement programs by such drought stricken countries as Ethiopia, resulting in the worsening of the situation of drought instead of alleviating it because of over population and over grazing.

Heathcote (1965) attributes desertification in Queensland and New South Wales to extensive ranching. He comments that the effect of extensive ranching in these two states has in some cases resulted in over grazing, which in turn resulted in soil erosion, and environmental degradation. Similarly, a study by Bharara (1982) argues that drought problems of India, besides being caused by natural factors, are also caused by human factors such as intensive agriculture involving land clearing. Morgan and Moss (1981) explain that drought among people under a pastoral system is caused by overgrazing which results in intensive browsing of grass in the areas concerned.

Glantz (1987) argues that drought in such places as Ethiopia, Sudan, Angola and Mozambique are not only caused by natural factors but also by internal wars and conflicts. He indicates that in parts of the country affected by these wars, people have stopped planting cash and food crops, and ceased practising soil conservation measures. On the other hand, the displacement of populations has also led to the clearing of ecologically sensitive areas.

Writing about pollution from industrial complexes, Glantz (1987) argues that most of the industrial complexes in West Africa emit large quantities of carbon dioxide and radioactive gases, which heat up the lower atmosphere resulting in a greenhouse type effect. Recently, the dumping of toxic wastes along the coasts of Nigeria and Ghana has been the source of conflict and controversy between West African states and European countries from where the toxic waste originated. Such wastes are claimed to have potency of not only destroying living organisms, but also inhibiting the growth of plants over a long period. The cessation of plant growth, and the exposure of bare soils to the natural elements of wind and water can further promulgate drought conditions (Economist, 1988).

2.3 Frameworks to Analyze Drought Management and Related Problems

It is pertinent to review in this section the various optimization models since the decision frameworks that seek efficient patterns of resource allocation employ such models (Thomas and Revelle, 1966). Further, given that mathematical programming models are capable of evaluating an infinite number of alternative patterns of resource allocation from a set description (Hazell and Norton, 1986), the review in this section is confined to mathematical programming models.

The mathematical programming models which have been used in the analysis of drought and related management problems can be classified into two broad categories. These are:

(i) deterministic programming models; and

(ii) stochastic programming models.

Further sub-divisions within these two categories are presented in Figure 2.4. A review of models listed in Figure 2.4 follows.

2.3.1 Deterministic programming models

Most deterministic models that are presented in the literature are linear programming models. The linear programming technique first developed by Dantzing in the 1940's, is generally defined as a mathematical technique that is used to allocate scarce resources to achieve an objective of maximizing revenue or minimizing costs (Lee, Moore and Taylor, 1985). This method is one of the most used programming techniques because of its easy application and adaptability. The detailed exposition of the merits and demerits of this technique is listed elsewhere (Dantzing, 1963; Bierman, Bonini and Hausman, 1977; Agrawal and Heady, 1972; Kwak, 1973; Anderson, Sweeney and Williams, 1979).

The general features of the linear programming models that have been used in drought management are:

(i) an objective function that defines the costs or returns of various drought management strategies to be maximized or minimized; and

(ii) a set of constraints that include apart from the usual resource endowments (land, labour and capital), drought related variables such as: soil moisture levels, evapotranspiration and the level of water in water bodies such as lakes and rivers.

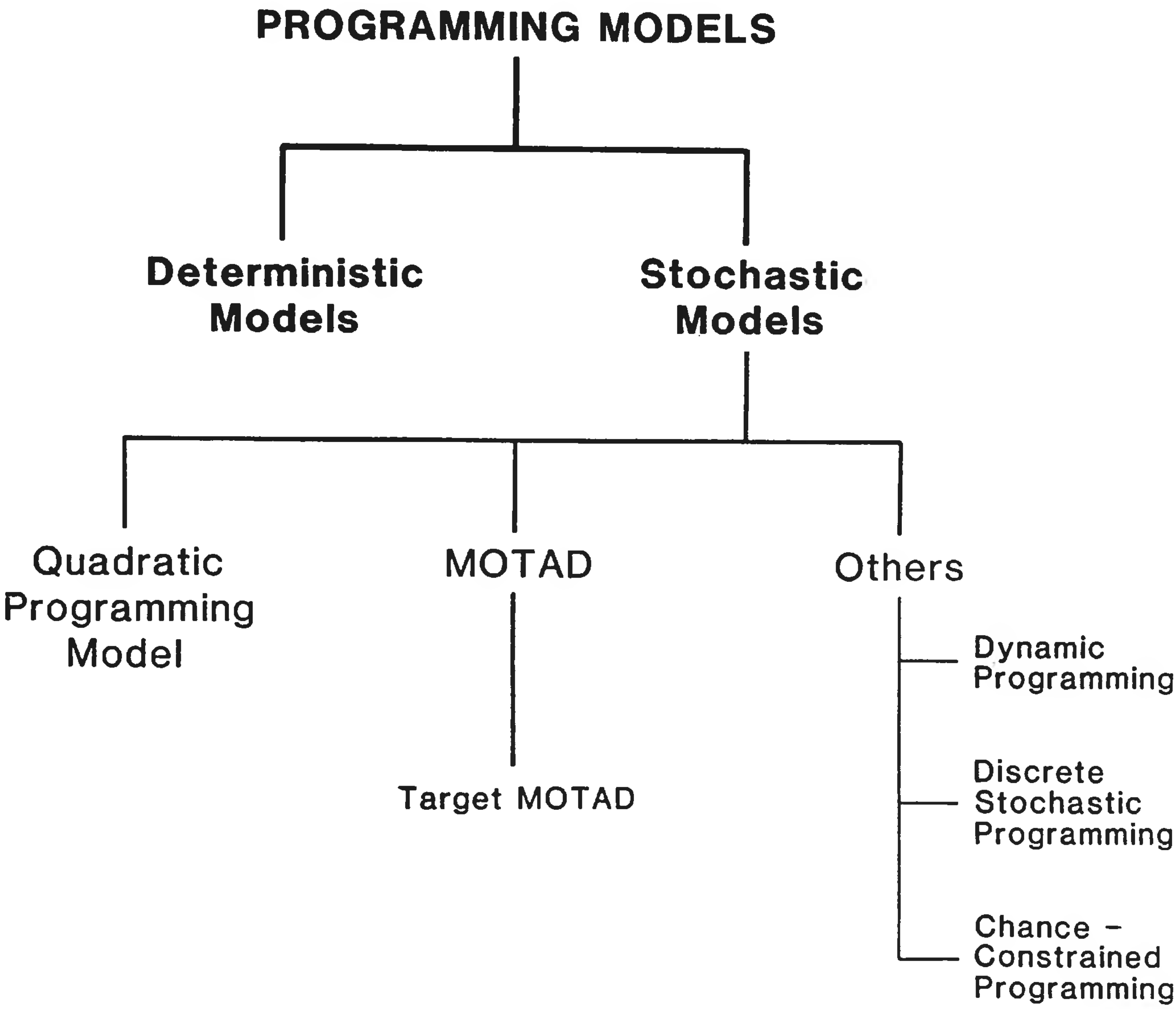

Figure 2.4 The types of programming models that are used in the analysis of drought problems.

The applications of linear programming models to problems involving water resources and land use planning are also relevant for drought management. This is because such models incorporate efficient cropping patterns and water allocation, both of which are drought management strategies. Some of the applications of linear programming models involving water allocation problems are given by Mobasheri and Harboe (1970) and Bredehoeft and Young (1970). With regard to land use planning, some applications of linear programming models have been made by McConnell (1983). He applies the linear programming model to find optimal strategies for maximizing revenue from crops grown under drought conditions. A study by Yaron and Dinar (1982), uses linear programming models to maximize farmer's revenue under drought conditions subject to the constraints of: soil moisture constraint, land, labour and capital. Tyagi (1986) uses a linear programming model to maximize revenue from irrigation projects in the state of Haryana in India. The constraints of this model include: soil moisture, losses of water from canal systems and the cost of pumping water from tubewells.

A study by Matanga and Marino (1979) uses a linear programming model to maximize revenue from growing several crops in California under drought conditions. The constraints specified of their model include a set of soil moisture constraints. A linear programming model was also used by Soltani-Mohamadi (1972) to maximize revenue from crops grown on irrigated land subject to water supply constraints, along with the usual constraint of land, labour and capital.

2.3.2 Stochastic models

Whilst deterministic programming models ignore the risks associated with drought, stochastic models explicitly recognize these risks. Hence, the aim of these models is not only to maximize the returns and or minimize the costs of adopting various drought management strategies, but also to minimize the risk associated with drought. A review of the relevant models is given below. Hence the methods by which risk is quantified for inclusion in the models become an important aspect of model formulation.

Quadratic programming

Quadratic programming was first applied by Markowitz (1959) to a portfolio investment selection problem. The general format of quadratic programming models is to optimize an objective function involving costs or returns and the variance of costs or returns. Since risk has been conventionally quantified in terms of variance of costs or returns, quadratic programming becomes a convenient tool to deal with risk. Hence, for example, a standard quadratic programming model in drought management can be described as:

Maximize Z = [Expected returns from adopting drought management strategies]

- β [variance of returns from adopting drought management strategies].

Subject to: resource endowment and drought related constraints.

In this formulation, β is a weight that transforms variance, namely the surrogate for risk to the same monetary dimension as expected returns, and is usually referred to as the risk aversion factor.

Quadratic programming has been applied to problems involving land use planning and the determination of cropping patterns. For example, Stovall (1966) has applied quadratic programming to a problem of cropping pattern in which a farmer is concerned with selecting a set of optimal farming practices which minimize the income variances from mean income because of variability in soil moisture stress. Another study by Johnson (1967) uses quadratic programming to a farm planning crop diversification problem. His diversification problem is concerned with finding an optimal strategy for combining risky agricultural production activities such that income variances and covariances are minimized.

Hazell and Scandizzo (1977) apply quadratic programming to a land use problem involving identification of optimal regional cropping patterns in Mexico. Several other scientists have used quadratic programming to land use problems involving the determination of cropping patterns (Wolfe, 1959; Theil and Van De Panne, 1960; Takhayama and Judge, 1964; Hall and Heady, 1968; Dillon and Anderson, 1971; and Hazell and Norton, 1986).

2.3.3 Minimization of Total Absolute Deviation (MOTAD)

Although quadratic programming is a convenient theoretical tool for incorporating risk, its applicability is limited due to inaccessibility to suitable algorithms and the complexities associated with computing the variance-covariance matrices as the measure of risk. However, a simplification and a more readily applicable transformation of the quadratic model was presented by Hazell (1971), where the nonlinearity due to the quadratic term was removed. In Hazell's version, risk was defined by mean absolute deviations instead of variance. This enabled the model to be linear instead of quadratic. These models referred to as MOTAD (Anderson, Dillon and Hardaker, 1977) are more readily applicable due to the wide availability of linear programming algorithms. For example, by applying MOTAD to a crop mix problem, Thomson and Hazell (1972) concluded that MOTAD was a more reliable risk programming technique than previously thought.

Thampapillai (1980) applied MOTAD to a land use problem involving crop mixes. The objective function for the MOTAD was to maximize expected revenue from various land use enterprises on a flood plain minus the cost of risk-taking due to flood events. The cost of risk-factors was defined as the absolute deviations from the mean revenue. These absolute deviations have to be weighted by a risk aversion factor. The constraints to restrict the maximization of his MOTAD model were defined by resource endowments on the flood plain.

O'Brien (1981) applies MOTAD to a crop mix problem. He specifies the objective function of the MOTAD model as maximization of expected revenue from growing rice minus the cost of risk which is expressed as a risk aversion coefficient times the absolute deviation of the net revenue above variable costs. This maximization of expected revenue is constrained by credit, labour and land.

MOTAD was also used by Apland, Barnes and Justus (1984) on a multiple objective programming problem involving two objectives. The aim of applying MOTAD to a grain farm was to analyze trade-offs between income for a tenant farmer and that for the landlord. Hence the objective function contains the expected income earned by the tenant as well as the landlord and the costs of risk taken by the tenant and the land lord. As in the other models the costs of risk were defined in terms of absolute deviations of income. The maximization of the objective function was subject to the constraints of land, labour and credit.

Other studies which have applied MOTAD to land use problems involving cropping patterns include: Hazell and Scandizzo (1974, 1977), Anderson, Dillon and Hardaker (1977) and Hardaker and Troncoso (1979).

2.3.4 Target MOTAD

Although MOTAD has been widely applied to land use problems, Tauer (1983), developed Target MOTAD as a modification of MOTAD. He describes Target MOTAD as an alternative mathematical programming model which is computationally efficient and generates solutions that meet the criterion of the second degree stochastic dominance (SSD) test.[1] If a model satisfies the SSD test, it follows that the possibilities of having increasing utility alongside risk aversion are eliminated. That is, a model satisfies the SSD test if the results do not imply the joint occurrence of increasing utility and risk aversion. Tauer (1983) demonstrates how Target MOTAD is similar to, and differs from MOTAD. For example, he points out that Target MOTAD is similar to MOTAD because both of them use a linear programming algorithm. However, he cites two properties to distinguish Target MOTAD from MOTAD. These are as follows.

(i) Target MOTAD is a two attribute model consisting of risk and return.

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1 Detailed explanation of the concept of stochastic dominance and the tests for stochastic dominance are given in Anderson, Dillon and Hardaker (1977) and Tauer (1983)

(ii) Unlike MOTAD which measures risk as absolute deviation of income from the mean income, Target MOTAD measures risk as absolute negative deviation of income from target income. Hence, Tauer (1983) describes Target MOTAD as more realistic than MOTAD because decision makers are normally concerned with not only maximizing expected revenue but also minimizing the deviations of expected returns below a critical or target level.

A detailed comparison between MOTAD and Target MOTAD was also done by Watts, Held and Helmers (1984) and McCamley and Kliebenstein (1987). Like Tauer (1983) they found that the results of the Target MOTAD satisfied the second degree stochastic dominance test.

Zimet and Spreen (1986) applied Target MOTAD model to a mixed farming enterprise. They specified the objective function as one which maximizes expected revenue from growing crops and raising livestock. This was subject to the constraints of land, labour, capital and annual deviation of income below target income.

Other studies which have theoretically dealt with Target Income are Romero and Rehman (1985) and Hazell and Norton (1986).

2.3.5 Other Programming Models

Other programming models are distinguished from programming models that have been reviewed above for the following reasons.

(i) The above programming models measure risks in terms of variation in income or gross margins. However, the other programming models to be reviewed soon, measure risks in the form of variation in resource supplies.

(ii) Further, the other programming models with the exception of one of them (chance constrained programming), assume decision making to follow a sequence of steps. This is not the case with programming models reviewed above.

The other programming models to be reviewed now are: dynamic programming, discrete stochastic programming and chance constrained programming. Each of these is briefly reviewed below.

Dynamic programming

Whilst the programming models reviewed above maximize revenue or minimize cost at one point in time and without taking into account the sequential nature of the decision process, dynamic programming models consider the interdependence of the various decision processes and maximize revenue or minimize cost for each decision process. Bellman (1957) who developed dynamic programming in 1957 did so to find solutions to complex programming problems which need to be optimized according to their various stages.

Since its inception, dynamic programming models have been applied to various problems especially those in the area of water allocation and cropping pattern. For example, among several studies that have applied dynamic programming models to water allocation problems are: Butcher, Haimes and Hall (1969); Dudley (1970); Dudley, Howell and Musgrave (1971a, 1971b); Dudley, Musgrave and Howell (1972); Jacoby and Loucks (1972); and Thampapillai (1980).

Among some studies which have applied dynamic programming models to land use problems involving cropping pattern are: Flinn and Musgrave (1967); Burt and Johnson (1967); Johnson and Moore (1967); Agrawal and Heady (1972); and Kennedy (1986). For example, Burt and Johnson, use dynamic programming to determine optimal crop mix in the Great Plains of the United States for wheat and for wheat following fallow. Their dynamic programming model contains two states, namely soil moisture level with land in wheat and soil moisture level with land in fallow.

Discrete Stochastic Programming

Although dynamic programming enables decision makers to optimize revenue and/or cost at every stage of the decision process, the "curse of dimensionality" is a common difficulty (Anderson, Dillon and Hardaker, 1977; and Hazell and Norton, 1986). On the other hand, discrete stochastic programming models account for these changes. Cocks (1968) developed discrete stochastic programming to solve linear programming problems where input-output coefficients of constraints are subject to probability distributions. According to him, the discrete stochastic programming method involves the simultaneous generation of all mutually exclusive possible outcomes and then transfers their variability into the objective function of the linear programming model.

Rae (1971a) describes discrete stochastic programming as a programming method that allows for sequential implementation of actions and occurrences of stochastic events. This implies that decision makers make current and future decisions on the basis of their past subjective experiences. This programming method has been applied to land use problems involving cropping pattern mixes. For example, Rae (1971b) applies this model to a cropping pattern problem which helps a farmer to decide what crops to grow in an environment in which the states of nature are uncertain.

Yaron and Horowitz (1972) have applied the discrete stochastic programming method to a farm planning problem which deals with identifying optimal cropping pattern under drought conditions.

O'Brien (1981) uses the discrete stochastic programming method to a rice production problem. According to him, the farmer's decision to plant rice is done after the occurrences of certain events such as rain, availability of labour and other agricultural inputs. Then he points out that subsequent decisions as to whether to apply fertilizer and weedicide are based on previous occurrences of events.

Chance constrained programming

The above reviewed programming models assume that solutions to the problems concerned are always feasible. This might not be the case due to certain stochastic factors. In fact, chance constrained programming recognized that feasibility cannot be guaranteed and that decision makers should aim at minimizing the risks of the occurrence of infeasibility (Hazell and Norton, 1986). This programming technique which was first developed by Charnes and Cooper (1959) is assumed to assist decision makers to minimize the risks of losing income by adopting strategies which guarantee some minimum income even during the worst periods. A detailed exposition of chance constrained programming is given by Charnes and Cooper (1963); Wagner (1969); Kirby (1970); Jagannathan (1974); Anderson, Dillon and Hardaker (1977); and Hazell and Norton (1986).

The application of this technique has mainly been in the area of reservoir water allocation problems. For example, Revelle, Joeres and Kirby (1969) expound a theoretical application of chance constrained programming to a water reservoir. They argue that the chance constrained programming problem would be to maximize the reservoir capacity for water storage subject to the condition that the volume of water in the reservoir should not fall below a certain predetermined level. Hence the risk lies in violating this predetermined level. A similar theoretical exposition of chance constrained programming problem is illustrated by Houck (1979).

Eisel (1972) has applied chance constrained programming model to a water allocation problem involving storage capacity of reservoir water for irrigation. The objective function of the chance constrained programming problem is to determine the capacity of an irrigation reservoir and to develop a reservoir operating policy that maximizes the time stream of net economic benefits from the system. The maximization of this objective function is constrained by meeting the specified irrigation target, guaranteeing the continuous supply of water from the reservoir for irrigation purposes and ensuring that any surplus water from the reservoir is spilled over.

2.4 Implications of the Literature Review

This section deals with the implications of the foregoing review of the definitions, causes and models of drought.

2.4.1 Implications of review of definitions of drought

Drought as defined by hydrologists, meteorologists and agriculturists was considered in Section 2.1. Hydrologists, define drought as a situation where the water level in a stream, river, lake or reservoir falls below a pre-determined level, which usually represents the mean average of a time series stream-flow data. This definition is relevant to the Lake Kariba District because the water for irrigation in the district is envisaged to come from Lake Kariba. Since the lake water is primarily used for hydro-electricity, the authorities do not allow any use of the lake's water if the depth of water falls below 475 metres. That is, according to electricity authorities, drought occurs if the Lake Kariba water levels fall below a depth of 475 metres. Hence, it is pertinent to specify the water level in Lake Kariba as a constraint in the decision models to be formulated in this thesis. This is done to ensure that the water to be used for irrigation does not render the depth of water in the lake to be less than 475 metres.

Meteorological drought is defined in terms of a dry period caused by a shortage of rainfall which in turn causes soil moisture stresses for plant growth. This definition is relevant for the Lake Kariba District because crop production in the area is constrained by shortage of rainfall (Scudder, 1962, 1985). Hence, rainfall becomes an integral component of the models used in this study. In the models that consider irrigation option, it would be pertinent to consider water allocated as a supplement to expected rainfall. Alternatively, in the models where irrigation is not used, cropping pattern is entirely dependent on rainfall.

Agriculturalists define drought in terms of crop water requirements or crop consumptive use. As illustrated subsequently, crop consumptive use becomes an important component of all models that are developed in this thesis.

2.4.2 Implications of review of causes of drought

In the foregoing review, two causes of drought, namely physical or natural causes of drought and human causes of drought were identified.

The physical or natural causes of drought which are relevant to the Lake Kariba District are topography and climate (Scudder, 1962, 1985). This study considers topography in formulating programming models for both the irrigation and the non-irrigation models. On the basis of topography, the study area is divided into zones. The amount of land for each zone for crop production is apportioned according to the physical characteristics of each zone. The proposed irrigation lay-out for the irrigation strategy also takes into account the topography of the study area.

According to climatic factors of the Lake Kariba area, there exist two distinct seasons in the area, namely the wet and the dry seasons (Scudder, 1962). Hence, the models developed in this study are also specified according to wet and dry seasons. To account for the stochastic nature of climatic factors in the study area, this study incorporates risk in the programming models of both seasons.

The human causes which are relevant to the Lake Kariba District are cropping patterns and government pricing and marketing policies which seem to favour cash crops (Watts, 1984 and Banda, 1985). Hence, the various government policies that have been regarded as relevant to the drought problem need to be incorporated in the decision model.

2.4.3 Implications of the review of models

As the literature suggests that incorporation of risk is important, the treatment of risk and uncertainty is an explicit objective of this study. Ideally quadratic programming model would be the best technique to use (Anderson, Dillon and Hardaker, 1977). However, quadratic programming is not adopted following the limitations noted in the review above. In particular, data for constructing the variance and covariance matrix is not available in the study area. This appears to be a more general problem because of the difficulties of defining risk in terms of variance and covariance.

Despite the wide application of MOTAD models to various land use problems (Anderson, Dillon and Hardaker, 1977 and Hazell and Norton, 1986), this study does not use the MOTAD model. This is because while MOTAD measures risk in terms of deviation of income from the associated mean income it does not measure the deviation from targets. Farmers in the Lake Kariba District are believed to measure risk as deviation of income from a fixed target income (University of Zambia Socio-Economic Survey, 1985). Hence, the pertinent models to be developed in this study are the Target MOTAD models. Limitations pertaining to the availability of data and appropriate algorithms preclude the testing of other relevant models such as discrete stochastic programming, chance-constrained programming and dynamic programming models.

The models used in this thesis are confined to two types of programming models, namely deterministic linear programming and the the Target MOTAD. The deterministic linear programming models are used despite the abstraction from the reality of a risky decision environment. This is done primarily to compare the strategies generated by the deterministic models with those generated by the stochastic models. An overview of these two categories of models in terms of the decision problem in the Lake Kariba District follows in the next chapter.

CHAPTER 3 DESCRIPTION OF THE STUDY AREA AND AN OVERVIEW OF DECISION FRAMEWORKS

Following the review of literature in Chapter 2, the main objective is to formulate and apply deterministic as well as stochastic models that would permit the elicitation of drought managment strategies. Given that these models have to be developed in the context of the Lake Kariba District, the salient features of this district are first described in Section 3.1. This is followed in Section 3.2 by an overview of the types of models to be formulated.

3.1 Location of the study area

The study area lies approximately 200 kilometres south of the Zambia's capital city Lusaka. It is bounded by Lake Kariba to the South and the escarpment to the North (Scudder, 1962). The nation of Zimbabwe lies to the east of Lake Kariba. The study area is part of a larger area that is commonly known as the Kariba or Gwembe valley. The valley extends about 400 kilometres stretching between the southern and the northern ends of Lake Kariba. Although the term Lake Kariba District is loosely used in this thesis, this study is confined to the northern section of the lake.

As shown in Figure 3.1, the study area lies in the valley of the Zambezi River and around the northern end of Lake Kariba which also happens to be the location of the Kariba Dam. The dam, as will be discussed in the next section, provides electricity for Zambia and Zimbabwe.

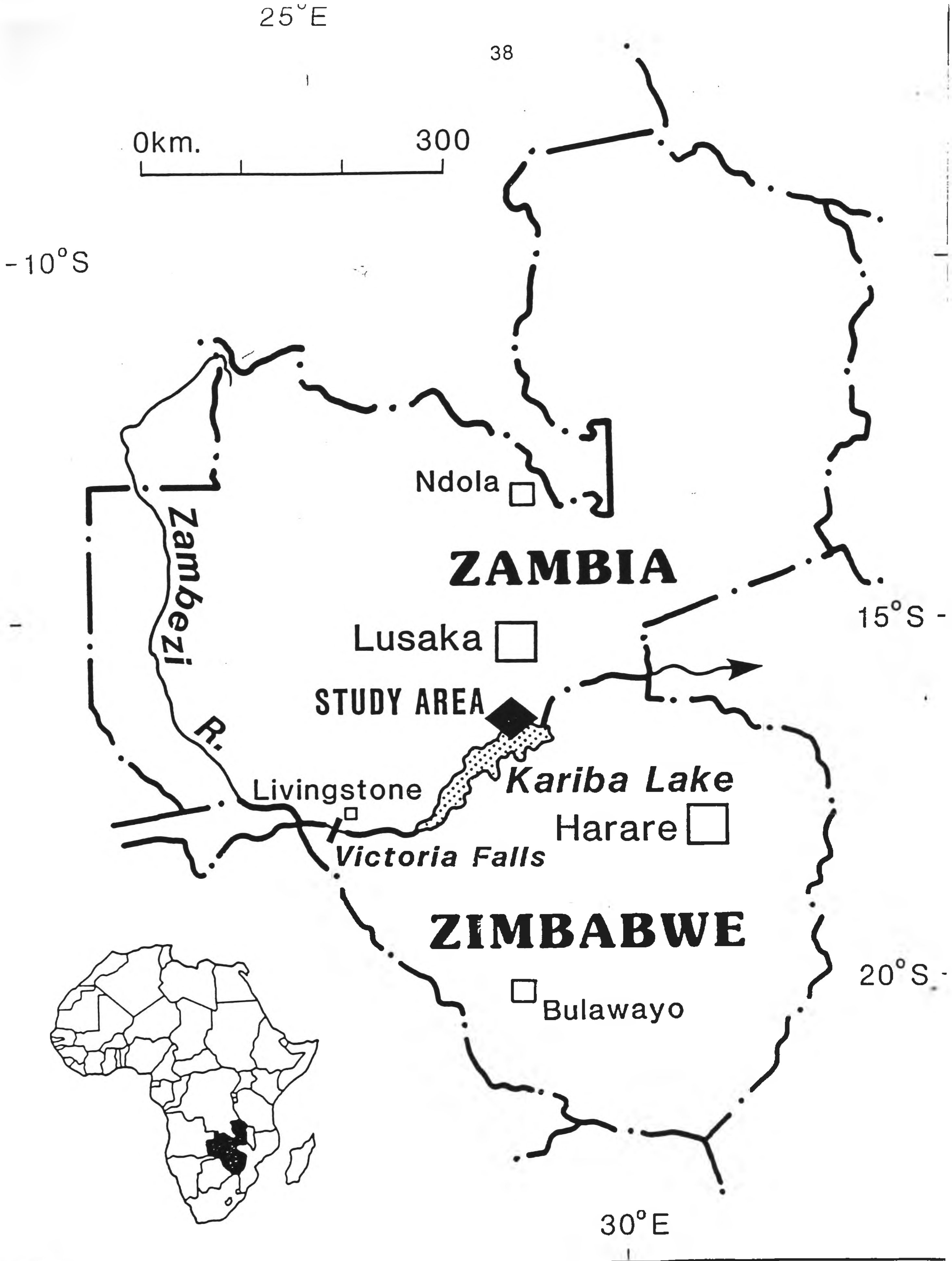


Figure 3.1 Location of the study area.

Source: Department of Lands, Lusaka, 1986.

3.1.1 The Kariba dam

The decision to build the Kariba Dam was taken in 1955, and construction work started in 1957. The construction of the dam was completed in 1959, and the formation of Lake Kariba was completed by 1962. The Kariba Dam is 200 metres high, 255km long and 20 km wide. The maximum depth of water in the lake has been estimated as 488 metres. The variation of water levels in the lake ranges from 488 to 477 metres. Further, since the formation of the lake, that is since 1962, the water levels have never fallen below the depth of 477 metres (Central African Power Corporation 1986). The physical aspects of the lake are dealt with in detail by Colson (1971), Gwembe Small-scale Irrigation Project Development Report (1985) and Banda (1985).

The dam was originally constructed to generate hydro-electricity for Zambia and Zimbabwe. However, in recent years interest has been expressed in utilizing surplus water from the lake for irrigation purposes (Clayton, 1985). The Central African Power Corporation (CAPCO), which is the organization charged with overseeing the operation of Lake Kariba, has indicated that for hydroelectricity generation the lake water level should be at least 475 metres deep, and that as long as the depth of lake water does not fall below 475, the lake water levels would be stable. Thus, the minimum water level of 475 metres can be used as a constraint in the formulation of irrigation models.

The electricity generated by the dam serves the needs of the mining complexes of Zambia and Zimbabwe. (See Figure 1A in Appendix 1). In this figure hydroelectric power stations and transmission lines under construction for Zimbabwe and Zambia are shown. According to Clayton (1985) the electricity generated by the dam exceeds the power demand requirements for these two countries.

For example, the combined demand for electricity from Zambia and Zimbabwe is approximately 14,092 GHW while the capacity of the Kariba Dam to generate electricity is approximately 19,425 GHW. Hence, it is plausible to assume that irrigation and hydroelectricity would not be conflicting enterprises as long as lake water levels are maintained at depths that are greater than or equal to 475 metres.

3.1.2 Soils and climate

The soils of Lake Kariba as described by Scudder (1962) are of pre-karoo and alluvial formation. Whereas the pre-karoo soils are at the foot of the escarpment, the karoo and alluvial soils are found between Lake Kariba and the escarpment and around the shores of Lake Kariba respectively. Some writers such as Maclean (1969), describe the soils of the Lake Kariba District as micaceous sandy loam and clay loam containing fine and medium subangular blocky structure.

Scudder (1962) divides the topography of Lake Kariba into three zones namely, (a) flat land from the shores of Lake Kariba to about 15 kilometres inland; (b) hilly and rugged land which starts at about 16 kilometres from the shores of Lake Kariba and extends to a further 20 kilometres; and (c) another stretch of flat land which starts at about 36 kilometres from the shore and extends to about 45 kilometres inland. This classification of land forms a convenient basis for defining zones in the formulation of land use models.

Since the Lake Kariba District lies in a valley, it is generally hot throughout the year with the hottest temperature reaching 40°C in the months of October and November. The cold months are between May and August, with the coldest month being July registering an average mean temperature of 15°C. The hot and cold temperatures of the Lake

Kariba area coincide with the general broad categories of the wet and dry seasons. While the wet season is from November to April, the dry season is from May to October. During the wet season the average temperature fluctuates between 30°C and 20°C. On the other hand, mean temperature during the dry season fluctuates between 40°C and 15°C (Scudder, 1962; Handlos and Williams, 1985).

The annual rainfall pattern in the Lake Kariba District in the wet season from 1952/53 to 1985/86 is illustrated in Figure 3.2. However, the monthly rainfall patterns during the same period are illustrated in Appendix II, Figures 2A to 4A. Figure 3.2 shows the mean average seasonal rainfall in the Lake Kariba District to be 721 millimetres. This figure also indicates that out of 34 years (1952/53 to 1985/86), values of rainfall above the mean average of 721 millimetres was observed only fifty percent of the time. The observations in Figure 3.2 and those in Appendix II indicate that rainfall during the wet season is free of any trend and does not follow a regular pattern of occurrence. However, it is important to note in Figure 3.2 that of the fifty percent of the time when rainfall was below the mean, at least 80 percent of the time, the values of rainfall were far below the mean. That is, a decline in rainfall of about 44 percent below the mean average of 721 millimetres (Sharma and Nyumbu, 1985). Normally, no rainfall is expected during the dry season but as Figure 3.3 shows, some rainfall occurs in this season in exceptional circumstances, which are of course rare. Moreover, mean rainfall in the dry season is very low, namely 21 millimetres. As a result, it is virtually impossible to grow crops during the dry season without irrigation. Comparison of annual rainfall between the wet and the dry seasons is illustrated in Figure 3.4.

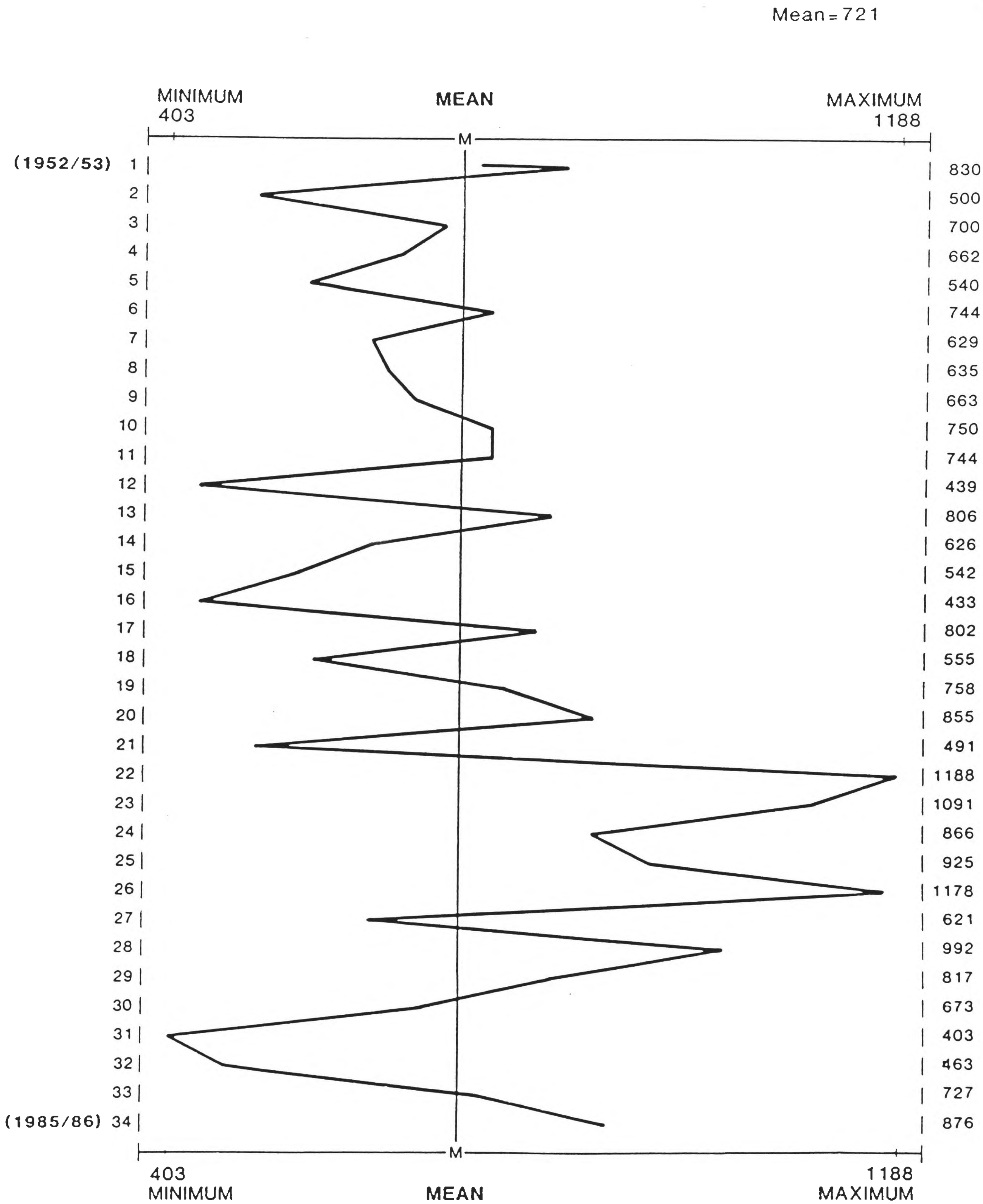


Figure 3.2 Annual rainfall pattern in the wet season for the Lake Kariba District 1952/53 - 1985/86

Source: Department of Meteorology, Harare, Several Issues.

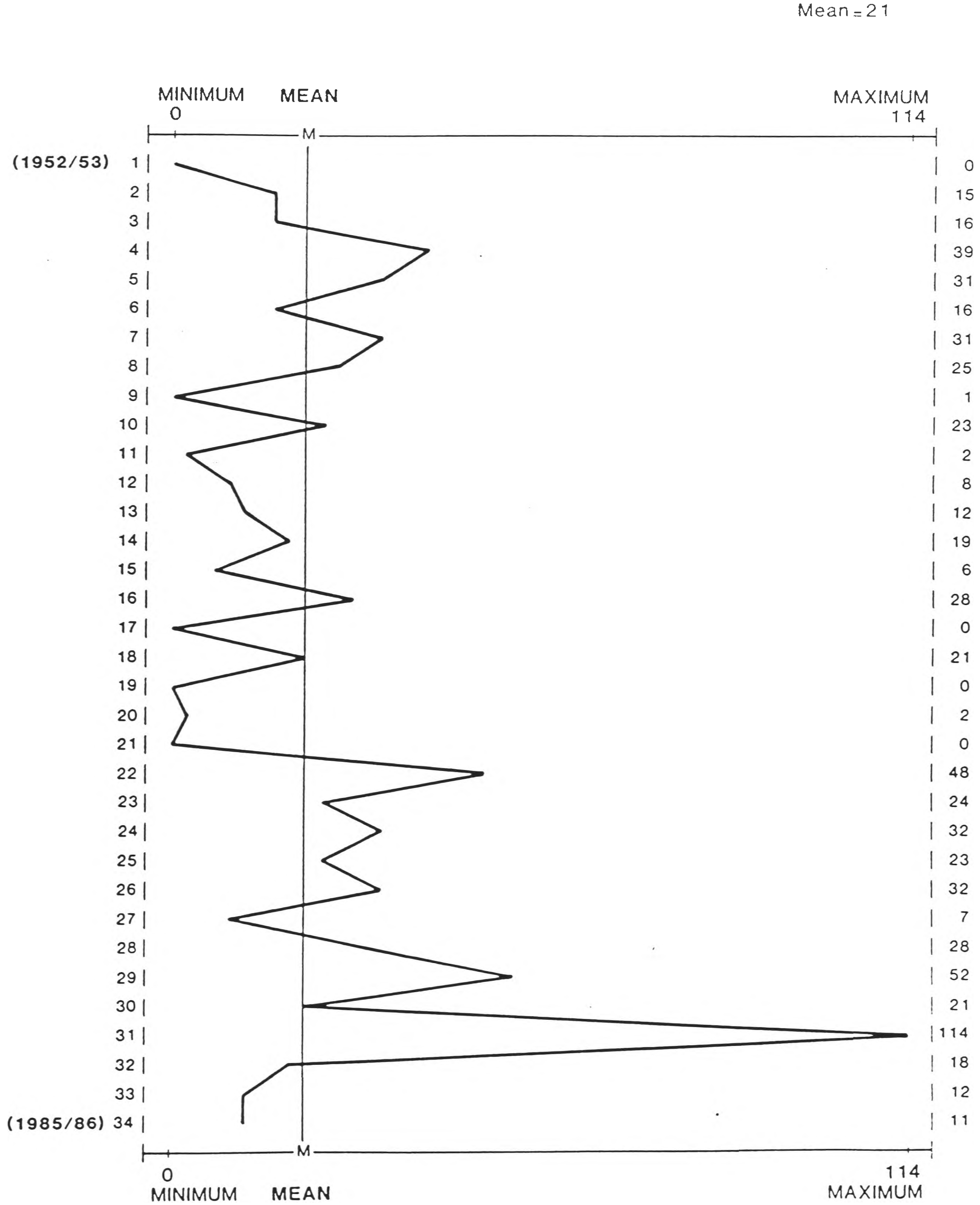
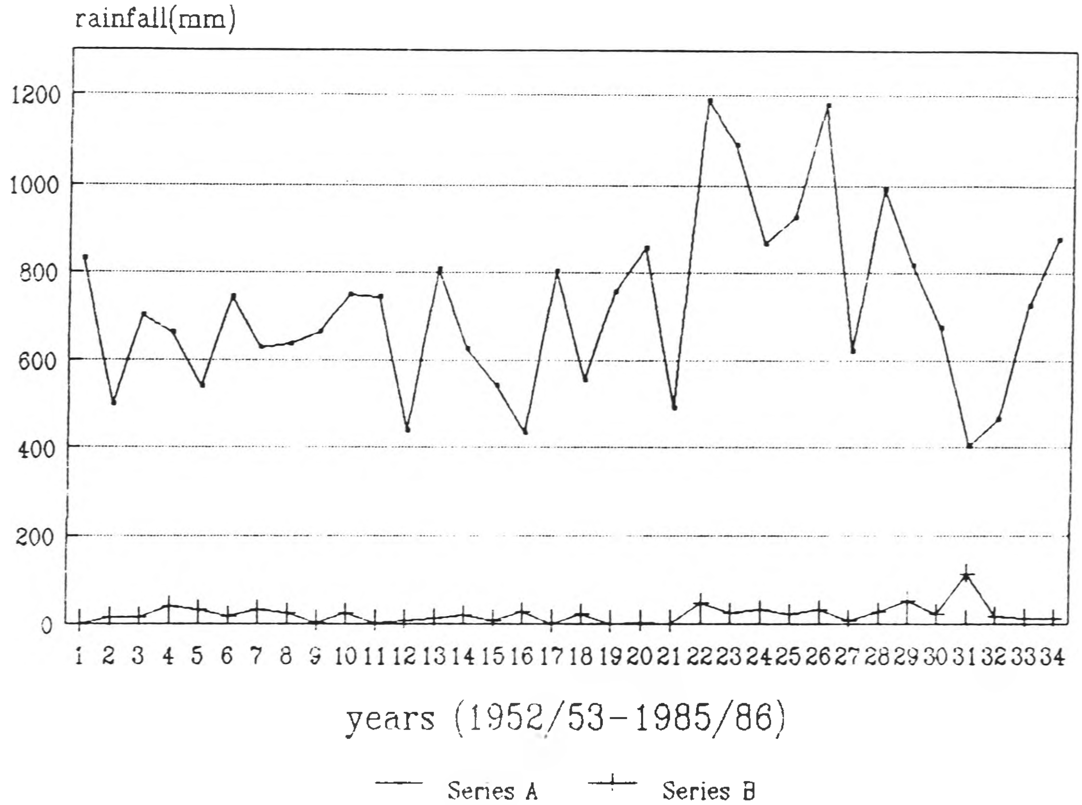


Figure 3.3 Annual rainfall pattern in the dry season for the Lake Kariba District 1952/53 - 1985/86

Source: Department of Meteorology (several issues).



A = Season1 B = Season2

Figure 3.4 Comparison of annual rainfall in the wet and dry seasons in the Lake Kariba District 1952/53 to 1985/86

Since the average number of persons per household in the study areas is about seven (Handlos and Williams, 1985), the number of hosueholds has been estimated as 12,000. These households are engaged into two types of economic activities, namely crop production and livestock rearing, (Scudder, 1962 and 1985; Banda, 1985; and Department of Agriculture, 1986). However, since livestock does not constitute a major economic activity, this study deals with only cropping activity.

Although various crops are currently grown in the study area, namely maize, cotton, sunflower and sorghum, the characteristic features in the region indicate that other crops, such as rice, soyabeans and wheat can also be grown. In fact long term plans are to introduce these other crops in the region (World Bank, 1983; Department of Agriculture, 1986).

3.1.3 Population and economic activity

The exact population of the study area is not known but it is estimated from the 1983 voters' register to be about 84,000 inhabitants (Siavonga Voters' Register, 1983).

Output of crops that are grown currently, namely maize, sunflower, cotton and sorghum is illustrated in Table 3.1. This table illustrates instability of output for all crops. For example, maize output fell from 15,400 metric tons in 1976 to 5,900 metric tons in 1982 and then rose again to 14,600 metric tons in 1985. Similarly, while no records have been kept for sorghum between 1976 and 1981 (due to the fact that no official pricing and marketing policy for sorghum existed in the country during that period) its output has also fluctuated, though there has been an overall increase in production. The same observations can be made of cotton and sunflower. All these

Table 3.1 **Crop output in the Lake Kariba District from 1976 to 1985 (Tons)**

Year	Maize	Sunflower	Cotton	Sorghum	Total Output	Output/ Person
1976	15400	1700	7600	---	24700	0.29
1977	11700	2900	8700	---	23300	0.27
1978	11500	1100	7100	---	19700	0.23
1979	15400	1400	14100	---	30900	0.36
1980	9000	1500	13000	---	34500	0.41
1981	8100	890	1500	---	10490	0.12
1982	5900	600	3300	900	9800	0.12
1983	7800	700	2200	1000	11700	0.14
1984	9800	700	5800	2900	19200	0.23
1985	14600	3100	20100	8900	46700	0.56

Source: Department of Agriculture, Choma (Several Reports) crops in Table 3.1 are grown during the wet season, and thus solely depend on rainfall which usually starts in November and ends in April. Hence, any analysis of instability in crop output in the Lake Kariba District, should examine the relationship between rainfall and crop output.

However, an indepth correlation analysis between rainfall and crop output is not possible due to lack of data. Records on crop output in the study area have been maintained only since 1976. Nevertheless, a visual examination of the data series on crop output and rainfall presented in Figure 3.5 reveals that there is a correlation between rainfall instability and crop output instability. Other authors (Scudder, 1962; Watts, 1984; Farag, 1985; Department of Agriculture, 1986) have also commented on such correlations.

Sorghum has always been a staple food crop in the Lake Kariba District (Scudder, 1962 and 1985). However, long-term plans are to educate the people in the area to adopt maize as an alternative staple food crop which is currently eaten when green and sold to urban dwellers and official marketing organizations. Cotton and sunflower are grown as cash crops. Long term plans are also to include rice, soyabeans and wheat to the list of cash crops (World Bank, 1983; Department of Agriculture, 1986).

Presently, the inhabitants of Lake Kariba District depend on sorghum as the staple food. Thus, any shortfall in the supply of sorghum is identified as famine. However, if they have income from other crops, e.g. maize, cotton and sunflower, they can use some of this income to purchase sorghum from other parts of Zambia to make up for the shortfall. It is in this connection that instability in income from cash crops should also be examined. The income derived from

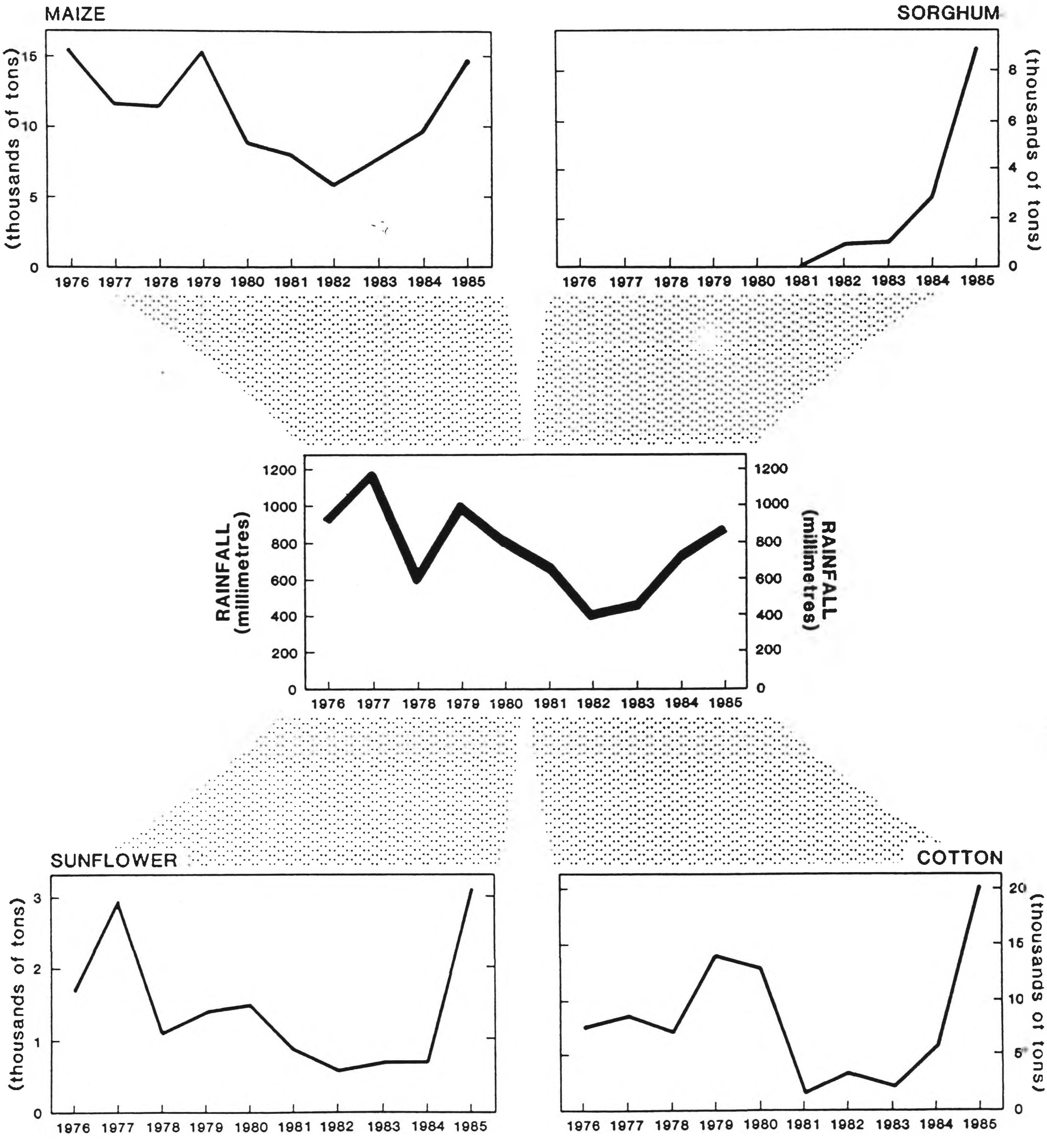


Figure 3.5 Relationship between crop production and rainfall in the Lake Kariba District.

maize, sunflower, cotton and sorghum is presented in Table 3.2, and the instability of income is clearly evident from this table.

Clearly the minimization of income and output instabilities due to the irregular nature of rainfall in the Lake Kariba District, is an important social objective for the region. Apart from stabilizing the levels of output and income, the avoidance of famine is a significantly more important objective. During periods of drought, the consumption of the population falls below the standards specified by health authorities in terms of calorific requirements. For example, Scudder (1962) has illustrated that periods of drought are also periods of famine. That is from the historical records of rainfall data it is plausible to suppose that crop output levels did not satisfy consumption calorific requirements for at least 17 years (out of the 34 year period). An examination of the crop output in Table 3.1 reveals that output during the period 1978-1985 satisfied calorific requirement only once out of ten years (see Table 3.3). As can be observed in Table 3.3, crop output in the Lake Kariba District between 1976 and 1985, fell short of the Zambian calorific cereal requirements of 2030 calories per day per person by an overall average of 37 percent. This short fall in calorific intake for the people of the Lake Kariba District is a clear indication of malnutrition and the problem is compounded by insignificant regional personal income as illustrated in Table 3.2. According to this table, personal incomes fall far short of average national income. Given that cropping is the major source of income, it is reasonable to assume that personal incomes are derived from crops. The highest personal income per year is 181 kwachas. This is equivalent to US$113 per year in 1976 prices and exchange rates. The lowest personal income is 17 kwachas per year; that is US$10.8 per year. Clearly such low incomes even during periods of

Table 3.2 Income from crops in the Lake Kariba District

Year	Maize	Sunflower	Cotton	Sorghum	Total	Income /head	National income/head
	k(000)					K	K
1976	2527	735	4502	0	7764	92	167
1977	1838	1257	8	0	3103	37	151
1978	1892	369	2713	0	4974	59	154
1979	2051	1748	3505	0	7304	87	130
1980	1166	440	3524	0	5130	61	138
1981	1537	178	1511	0	3226	38	113
1982	410	111	1032	9	1562	19	N/A
1983	689	141	588	17	1435	17	N/A
1984	882	373	362	597	2214	26	N/A
1985	14201	1347	7009	2665	15222	181	N/A

Source: Department of Agriculture, Choma (Several Issues) and Central Statistics Office, Lusaka, 1986.

Table 3.3 Total maize and sorghum production in terms of calorific requirements in Zambia

Year	Total maize & sorghum	Calorific values maize & sorghum*	Calorie per person per day	National calorie requirement	Deviation of calorie per person from national calorie requirement
	(Tons)	(Million)	(K.cal)	(K.cal)	(Percent)
1976	15400	53900	1758	2030	-13
1977	11700	40950	1336	"	-34
1978	11600	40600	1324	"	-35
1979	15400	53900	1758	"	-13
1980	9000	31500	1027	"	-49
1981	8000	28000	931	"	-54
1982	6800	23800	776	"	-62
1983	8800	30800	1004	"	-51
1984	12800	44800	1461	"	-28
1985	23400	81900	2671	"	+31

Source: Department of Agriculture (1986), National Food and Nutrition Programme of Zambia (1974) and Monthly Digest of Statistics (1982). *Note: Calorific values were calculated by multiplying column 2 by 3.5 million. This is because one metric ton equals 3,540,000 k.cal (Demographic Year Book 1986) high rainfall and crop output, conform to the definition of absolute poverty (Meier, 1984). Although the objective of this thesis does not concern the analysis of poverty and inequality, the objectives of raising agricultural output to avoid famine and stabilizing output could also result in raising the levels of personal incomes and lowering poverty (Hay, 1988; Reardon , Matlon and Delgado, 1988)

The implementation of irrigation programmes could serve to achieve the objectives of stabilizing output and avoiding famines. As indicated above, the aim of this thesis is to evaluate the option of having irrigation as against not having irrigation, and a broad description of the frameworks that permit this evaluation is presented below.

3.2 An overview of decision frameworks

This section presents and describes an overview of three frameworks which could help to identify optimal drought management strategies in the study area. The description of these frameworks is presented in the form of flow-charts.

The first flow-chart, labelled Figure 3.6 includes a deterministic linear programming model and pertains to the "with irrigation" option. The central assumption in this model is that risks and uncertainty due to the stochastic nature of rain-fall are non-existent because of irrigation and the adequate availability of water from Lake Kariba. Despite periods of low rainfall, the level of water in the Lake Kariba is sustained due to a large catchment area comprising of several rivers and streams (Handlos and Williams, 1985; Sharma and Nyumbu, 1985). The certainty assumptions are relaxed and uncertainty is introduced, in the second framework, which also pertains to the "with irrigation option". This is presented in Figure 3.7.

The final flow-chart, which is presented in Figure 3.8, also illustrates a stochastic framework. But this framework pertains to the "without irrigation" option. The rationale of each of these frameworks is briefly described below. Each of these frameworks is developed on the premise that drought management policies have to be derived for a six year planning period. The choice of six years is governed by existing patterns of decision making in Zambia. For example, Zambia's national development plans run for six years (National Commission for Development Planning, 1986) and the University of Zambia study found that the farmers in the study area maintain their overall cropping pattern at least for six years before adopting new ones (The University of Zambia Study, 1984).

3.2.1 A deterministic framework for the "with irrigation" option

This framework is presented in Figure 3.6. The sequence of events described in this Figure pertains to one year of agricultural production. Since the planning period for the formulation of production strategies has been nominated as six years, the above sequence of events is repeated six times. The main components of the model are:

(a) a rainfall simulator;

(b) a deterministic linear programming model for each season; and

(c) a monitor to record lake water levels.

The simulation of rainfall is carried out using the Monte Carlo technique and is based on rainfall records for the period (1952/53 to

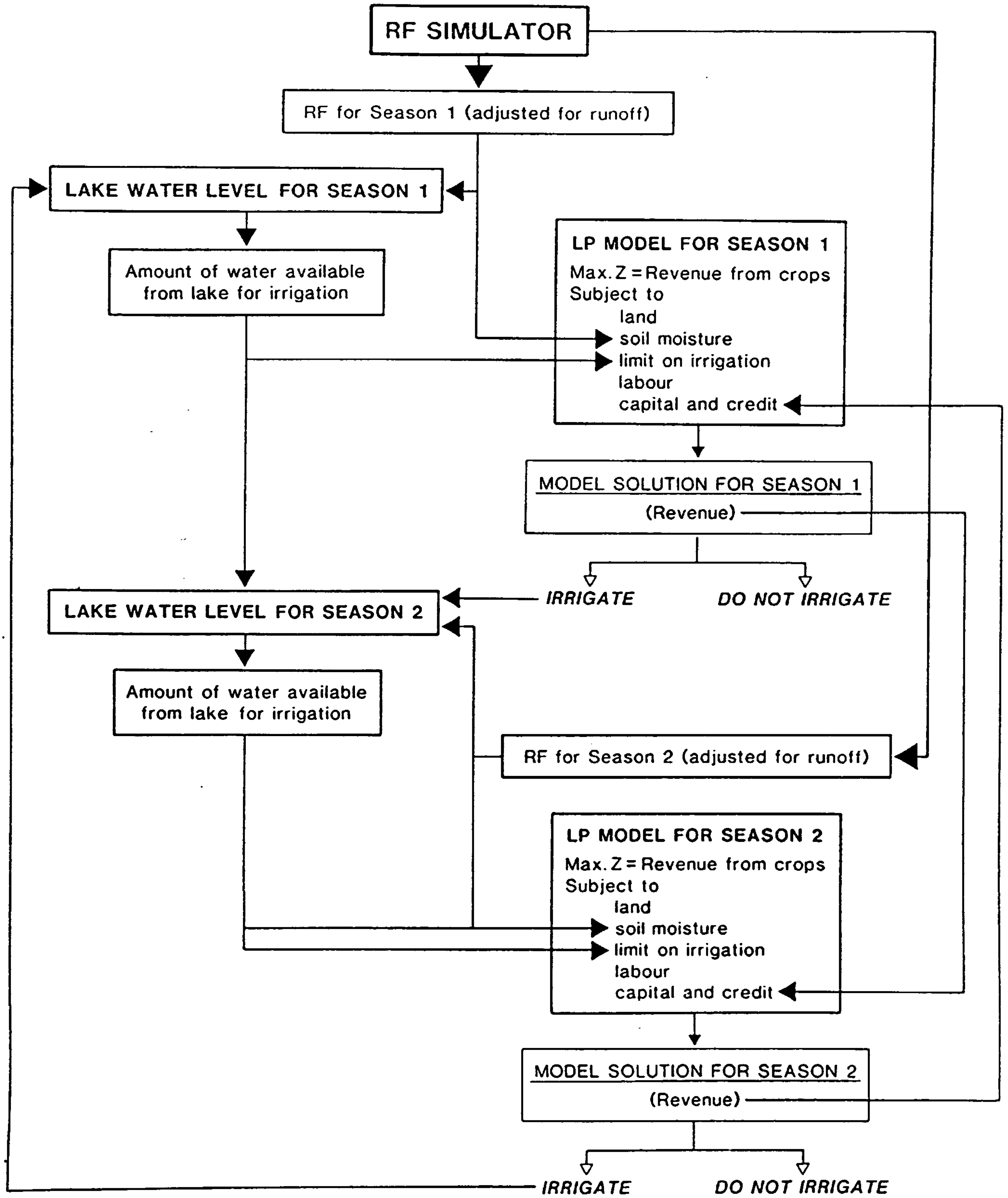


Figure 3.6 The deterministic framework for the "with irrigation" option

1985/86. Following Sharma and Nyumbu (1985), the simulated value of rainfall is reduced by eight percent to allow for run-off losses.

Consider first the initial planning year. The adjusted value of simulated rainfall for the first (wet) season is defined as the soil moisture constraint of the first season's linear programming model. The value of rainfall also influences the level of water in the lake. The availability of water for irrigation in the linear programming model is now estimated, taking into account the restriction that lake water level must be maintained at depths that exceed 475 metres.

The linear programming model for the first season of the initial year is as follows.

Maximize Revenue	=	[Gross margin from growing crops]
	-	[Cost of irrigation]
	-	[Cost of credit]

Subject to: land, labour, soil moisture, water availability for irrigation and capital.

Hence, the model solution for the first season reveals:

(a) the mix of crops to be grown;

(b) the amount of lake water to be used for irrigation; and

(c) the amount of credit to be given to the farmers.

The linear programming model for the second (dry) season is similar to that of the first season. The soil moisture constraint is defined by the simulated value of rain for the second season. The availability of irrigation water in the second season is influenced by the simulated value of rainfall as well as the amount of water drawn for irrigation during the first season. Further the amount of capital available during the second season is estimated on the premise that thirty percent of the revenue earned during the previous season is reinvested (Planning Division, 1984). The model solution of the second season will now influence the formulation of the model for the first season of the second year, along with the relevant value of simulated rainfall. Thus, successive linear programming models are sequentially solved until the model solution for the second season of the final planning year has been derived.

3.2.2 A stochastic framework for the "with irrigation" strategy option

The components of this framework are presented in Figure 3.7. Following the review in Chapter 2, the optimizing model used in this framework is a Target MOTAD model. Since, rainfall and drought conditions cannot be predicted with certainty, the risk taken by farmers in their production activities must be included in the analysis. Crop losses due to drought are assumed to be a random variable with a given distribution. The mean of this distribution, namely the expected value of drought losses is assumed to be the losses due to drought during a specific period. Following Tauer (1983), McCamley and Kliebenstein (1987), the risk taken by farmers can be described by the dispersion of losses below a prespecified target income and is treated as an explicit cost. Whilst in Figure 3.6, the sequence of events is repeated six times to generate strategies for the six year period, in this figure, this is not done even though it contains a similar sequence of events. This is because expectations are taken over a six year period. The completion of the sequence of events would depict the strategy to be adopted each year of the six year period. The main components of the model are:

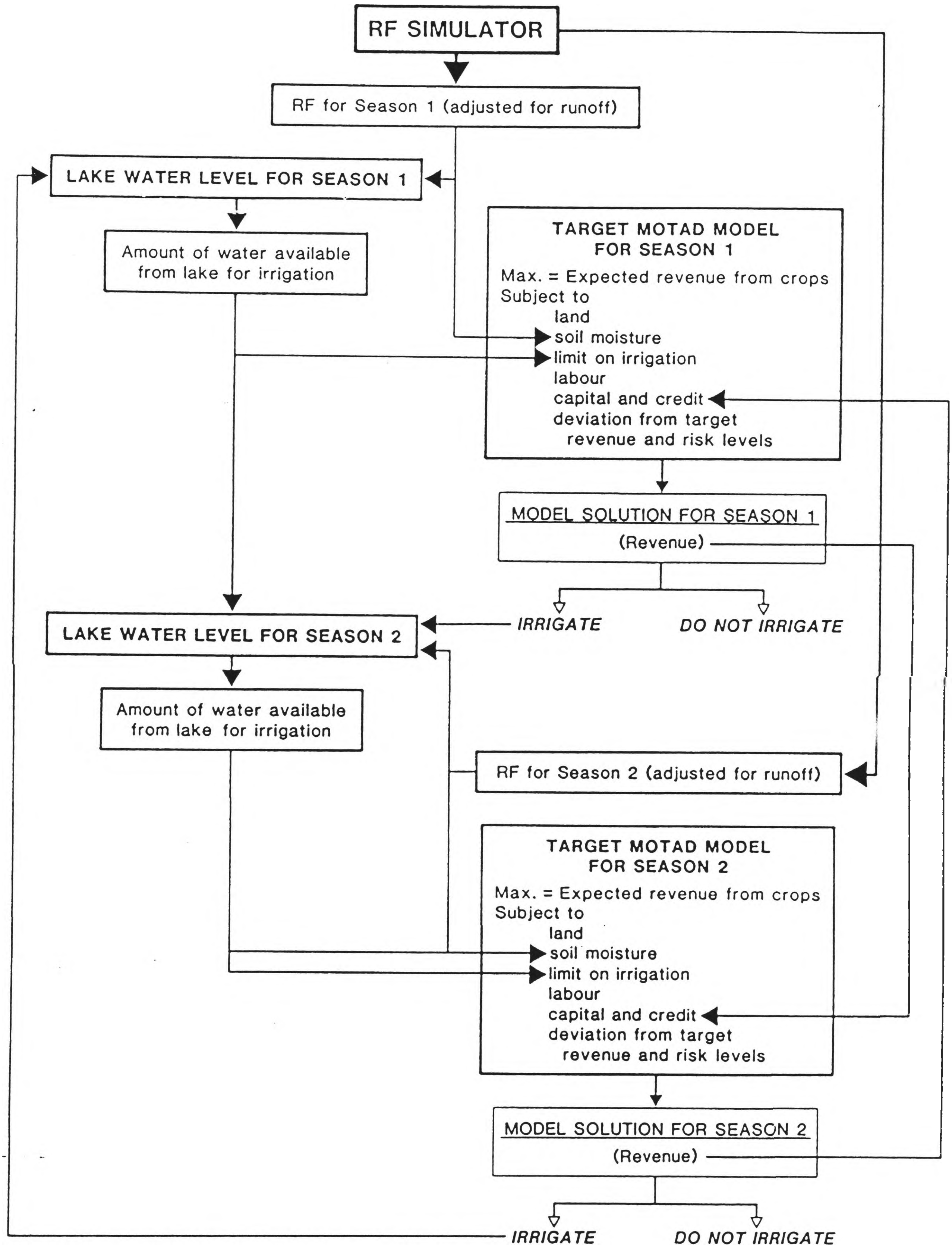


Figure 3.7 The stochastic framework for the "with irrigation" option

(a) a rainfall simulator;

(b) a Target MOTAD model for each session; and

(c) a monitor to record lake water levels.

Similiar to the framework of Figure 3.6, the same set of procedures are used to simulate rainfall and calculate run-off and are used in the Target MOTAD model.

The Target MOTAD model for a given season is as follows:

Maximise Revenue	=	[Expected value of gross margin from cropping]
	-	[Cost of irrigation]
	-	[Cost of credit]

Subject to: the constraints of land, labour, soil moisture, capital and credit, limit on irrigation, deviation from target revenue and risk levels.

Hence the model solution for each season reveals:

(a) the mix of crops to be grown;

(b) the amount of lake water to be used for irrigation; and

(c) the amount of credit to be given to the farmers.

As with the framework in Section 3.2.1, the solution of the model for the second season is contingent on the solution of the model for the first season.

3.2.3 A framework for the "without irrigation" option

This framework which is used, for deriving the "without irrigation" strategy is presented in Figure 3.8. The optimizing model

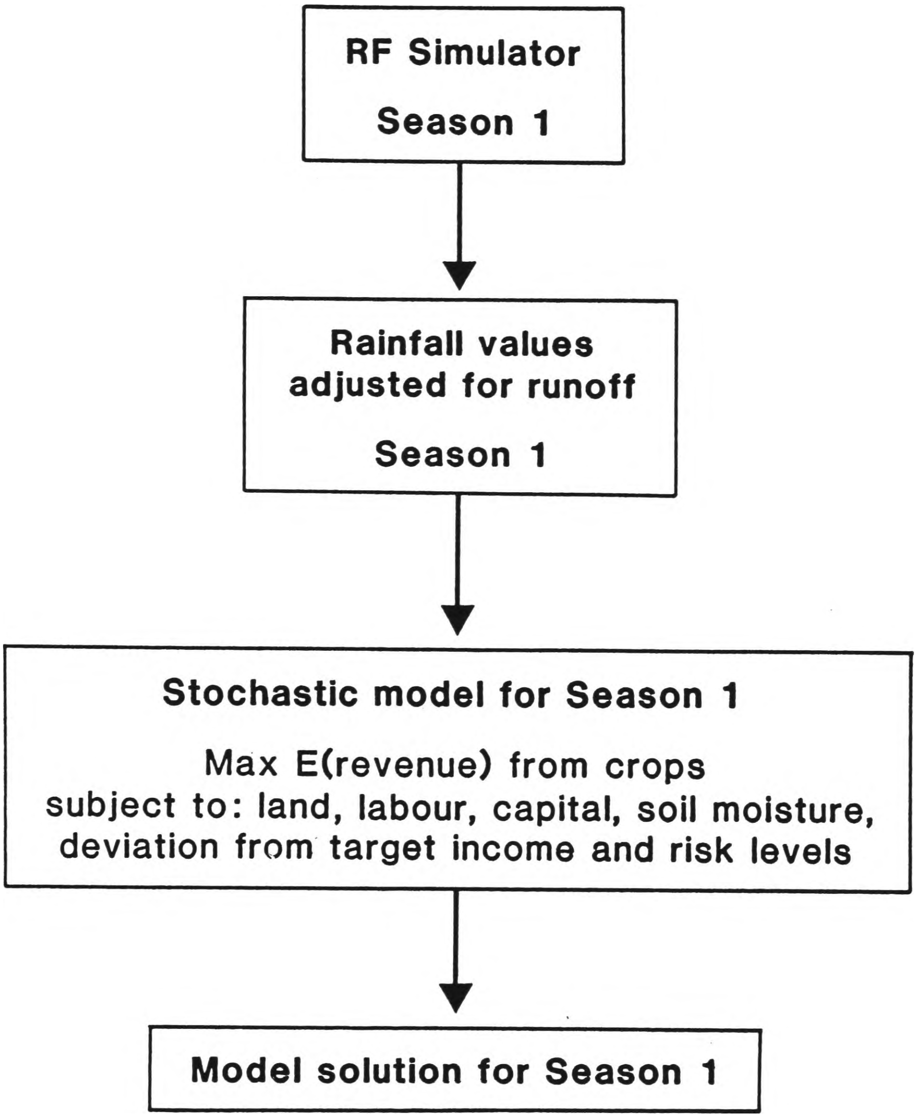


Figure 3.8 The stochastic framework for the "without irrigation" option

in this framework is also a Target MOTAD model. In this context, the community has to rely on rainfed agriculture. Hence, the formulation of models and the demonstration of production strategies is confined to one season only, namely the wet season.

As with the Target MOTAD model of the "with irrigation" strategy, the model for this option also considers expectations over a six year period. In this period, the sequence of events would depict the strategy to be adopted each year of the six year period.

The main components of the framework for the "without irrigation" are as follows:

(a) a rainfall simulator; and

(b) a Target MOTAD model for the wet season.

The Target MOTAD model for the wet season in the "without irrigation" option is similar to that of the model presented in Section 3.2.2 with the exception that the cost of irrigation and lake water levels are excluded from the objective function and the constraint set respectively. The model is as follows:

Maximize Revenue = [Expected value of gross margin from cropping]

- [Cost of credit]

Subject to: the constraint of land, labour, credit capital, soil moisture, deviation from target income and risk levels.

Hence, the model solution for the "without irrigation" Target MOTAD reveals:

(a) the mix of crops to be grown; and

(b) the amount of credit to be given to farmers.

The specification and empirical estimation of the models considered in this section will be presented in the next chapter.

CHAPTER 4 FORMULATION OF THE DECISION FRAMEWORKS

To recapitulate the objectives of this study are to:

(i) formulate frameworks for the "with irrigation" and the "without irrigation" strategies;

(ii) empirically demonstrate the applicability of these frameworks to the study area;

(iii) illustrate management strategies that are pertinent to the study area; and

(iv) analyse the trade-offs between the income maximization and the food stability objectives.

An overview of the frameworks that would serve to achieve these objectives was presented in Chapter 3. A detailed description of the components of these frameworks is now presented.

4.1 The deterministic framework for the "with irrigation" option

The main components of this framework are:

(i) a rainfall simulator;

(ii) a deterministic linear programming model; and

(iii) a monitor of lake water levels.

The conceptual basis for the formulation and application of each of these components are first considered in turn. This is followed by the empirical definitions of the relevant components.

4.1.1 The rainfall simulator

The rainfall simulator provides simulated rainfall values for the Lake Kariba District. The simulation was done by using the Monte

Carlo method (Lee, 1983). The rainfall data that were used per;tain to the period 1952/53 to 1985/86, and this data were distinguished in terms of wet and dry seasons. Such a distinction facilitates the formulation of land use for each of the two seasons. Although 34 years of actual rainfall data are not large enough (De Neufville and Marks, 1974), this was the only data that were available at the time of research. To compensate for this sparseness of data, the rainfall values for each season were simulated one hundred and eighty times. Both the actual and simulated rainfall data are presented in Tables 1A to 3A in Appendix III.

After simulating actual rainfall data of each season for one hundred and eighty times, thirty scenarios were created from this simulated data. Each of these scenarios represents a planning period of six years and hence contains six sets of randomly selected simulated rainfall values. Each set which is subsequently defined as a "state of nature" has two rainfall values, one for the wet season and the other for the dry season. Thus it is assumed that these thirty scenarios are representative enough for possible variations in the pattern of rainfall in the district during a given six year plan period.

In order to assess the validity of using the simulated values, it was necessary to test whether the simulated rainfall values and the observed values come from the same population. For this purpose the simulated data were subjected to the analysis of variance (ANOVA) (Harrison and Tamaschke, 1984). The results of this test which are reported in Tables 4A and 5A of Appendix III indicate that the actual and simulated rainfall data come from the same population.

Following Sharma and Nyumbu (1985), the simulated rainfall values are reduced by eight percent to allow for run-off losses in the study area. Then the adjusted values of simulated rainfall are used to determine soil moisture levels and lake water levels. Both of these are used in the linear programming model which is considered next.

4.1.2 Deterministic linear programming model

A deterministic linear programming model was formulated for each of the two seasons. However, the components of the models are the same regardless of the season.

The objective function pertains to the maximization of gross margins from seven crop production activities, namely maize, cotton, sunflower, soyabeans, sorghum, rice and wheat. Gross margin is defined as the difference between gross revenue and variable costs. The cropping activities were selected on the basis of stated government policies towards the region and recommended agronomic factors concerning the production of crops in the Lake Kariba District (World Bank, 1983; AGRINDCO, 1987; and Department of Agriculture, 1986).

The constraints of the model are the availability of: land, labour, cash capital, soil moisture and water for irrigation. It is assumed that production of these seven crops within the limitations of the above five constraints has to take place in five zones of the study area. The basis for defining these zones is described below.

For purpose of expository convenience, the specification of the objective function and that of the constraints is dealt with individually. The overall deterministic linear programming model is then assembled. Consider first the linear programming model for the first season, which is the wet season.

Objective Function

It is assumed that the crop production and irrigation activities involve credit. Hence, the following variables are pertinent and are defined as follows:

X_{qij} represents the area of land in hectares devoted to crop j that is grown during season i, in zone q;

C_{qij} represents the gross margin per hectare of crop j that is grown during season i in zone q;

W_{qij} represents amount of water in hectare millimetres supplied to crop j that is grown during season i in zone q;

b_{qij} represents the amount of cash credit in kwacha obtained for crop j that is grown during season i in zone q;

k_{qij} represents the cost per hectare millimetre of irrigating crop j that is grown during season i in zone q; and

I_{qij} represents annual interest charge on the cash credit that was obtained for crop j that is grown during season i in zone q;

where: $q = 1,...,5$

$i = 1,...,2$

$j = 1,...,7$

Thus, gross margin in season 1 for seven crops in five zones when specified in summary form becomes:

$$\text{Max } Z = \sum_{q=1}^{5} \sum_{j=1}^{7} C_{qij} X_{qij} - \sum_{q=1}^{5} \sum_{j=1}^{7} k_{qij} W_{qij} - \sum_{q=1}^{5} \sum_{j=1}^{7} Ib_{qij}, \qquad (4.1)$$

where the decision or policy variables are: X_{qij}, W_{qij} and b_{qij}.

Constraints of the linear programming model

Each of the five constraints is now considered in turn.

Land Constraint

The specification of the land constraint for season i is as follows: Let the amount of land available for crop production in a given zone be denoted as L_q. Hence, all land use enterprises compete for the use of this land area L_q. Let the amount of land required to produce one unit of crop j during season i in zone q be denoted as a_{qij}.

Thus, the land constraint is:

$$\sum_{q=1}^{5} \sum_{j=1}^{7} a_{qij} X_{qij} \leq L_{qi} \tag{4.2}$$

Labour constraint

A statement of the amount of labour required per hectare to produce crop j, in zone q, during season i is written as:

$$\sum_{q=1}^{5} \sum_{j=1}^{7} A_{qij} X_{qij} \leq 1_{qi} \tag{4.3}$$

where:

1_{qi} is amount of labour in man-days that is available in zone q; and A_{qij} represents the amount of labour in man-days that is required to produce one hectare of crop j, during season i, in zone q.

Credit constraint

It is assumed that credit simply involves the borrowing of cash, although some credit is provided as inputs.

Let, Q_{qij} represent the amount of cash capital required for the production of one unit of crop j during season i, in zone q; and let M_{qi} represent the amount of cash capital that is available at the start of season i, in zone q. Given that b_{qij} represents the amount of money borrowed during season i for crop j, in zone q, the credit constraint is:

$$\sum_{q=1}^{5} \sum_{j=1}^{7} Q_{qij} X_{qij} - \sum_{q=1}^{5} \sum_{j=1}^{7} b_{qij} \leq M_{qi} \qquad (4.4)$$

The meaning of (4.4) is that the amount of cash capital that is required for the production of crop j, during season i in zone q, should be less than or equal to the sum of: the amount of cash capital available at the start of season i in zone q, and the amount that is borrowed by farmers.

Soil moisture constraint

Variables in the soil moisture constraint are defined as follows. Let R_{qi} represent the amount of rainfall after subtracting the run-off from the simulated rainfall values measured in hectare millimetres in zone q during season i; and let t_{qij} represent in millimetres the per hectare crop consumptive use for crop j, during season i, in zone q.

In summary form the soil moisture constraint is specified as:

$$\sum_{q=1}^{5} \sum_{j=1}^{7} t_{qij} X_{qij} - \sum_{q=1}^{5} \sum_{j=1}^{7} W_{qij} \leq R_{qi} \qquad (4.5)$$

Recall that "consumptive use" refers to a crop's water requirement and W_{qij} represents the amount of water that is drawn for irrigation. Hence, the meaning of (4.5) is that water requirement for crop j during season i in zone q has to be less than or equal to water supplied by rainfall and irrigation.

Irrigation constraint

The irrigation constraint is included in the linear programming model to ensure that the amount of water drawn for irrigation does not violate the threshold level of the lake water depth of 475 metres that is required by the hydroelectricity scheme. Hence, the specification of this constraint is as follows. Let: LW_i represent the amount of water available above the threshold depth of 475 metres in season i. So, in summary form the irrigation constraint can be written as:

$$\sum_{q=1}^{5} \sum_{j=1}^{7} W_{qij} \leq LW_i \tag{4.6}$$

Thus, (4.6) states that the amount of water drawn for irrigation should not exceed the amount of water that is above the threshold level.

The overall model for season i can be assembled as follows:

$$\text{Maximize Revenue} = \sum_{q=1}^{5} \sum_{j=1}^{7} c_{qij} X_{qij} - \sum_{q=1}^{5} \sum_{j=1}^{7} k_{qij} W_{qij} - \sum_{q=1}^{5} \sum_{j=1}^{7} Ib_{qij}$$

Subject to:

$$\sum_{q=1}^{5} \sum_{j=1}^{7} a_{qij} X_{qij} \leq L_{qi},$$

$$\sum_{q=1}^{5} \sum_{j=1}^{7} A_{qij} X_{qij} \leq l_{qi},$$

$$\sum_{q=1}^{5} \sum_{j=1}^{7} Q_{qij} X_{qij} - \sum_{q=1}^{5} \sum_{j=1}^{7} b_{qij} \leq M_{qi},$$

$$\sum_{q=1}^{5} \sum_{j=1}^{7} t_{qij} X_{qij} - \sum_{q=1}^{5} \sum_{j=1}^{7} W_{qij} \leq R_{qi},$$

$$\sum_{q=1}^{5} \sum_{j=1}^{7} W_{qij} \leq L_{qi}; \text{ and}$$

$$X_{qij},\ b_{qij}, W_{qij} \geq 0 \qquad (4.7)$$

The above linear programming model yields an optimal crop mix solution that maximizes gross margins during a given season.

The linkages between the models of the two seasons were explained in Chapter 3. To recapitulate; for example, the availability of irrigation water in a given season is influenced by the simulated value of rainfall of that season and may also be influenced by the amount of water that was drawn for irrigation during the previous season. Likewise, the amount of capital available during a given season is estimated on the premise that thirty percent of the revenue earned during the previous season is saved. Thus the model solution of a given season will influence the formulation of the model for the next season. Hence, successive linear programming models are sequentially solved until the model solution for the second season of the final planning year has been derived.

4.1.3 The monitor to record lake water levels

As indicated, the monitor on lake water levels is used to define the amount of water that is available for irrigation, subject to the restriction that the depth of water in the lake does not fall below a critical level. Hence, the primary rate of this monitor is the provision of information for the definition of the irrigation constraint that was described above.

The amount of water that is available at the beginning of a season would usually be influenced by the amount of water that was drawn for irrigation during the previous season, and the amount of rainfall that the district receives during and before a given season. However, the lake has a large catchment area (see Figure 5A in Appendix IV) and the lake itself is a large body of water. Hence, hydrologists indicate that the availability of water for irrigation would become critical only if the amount of water drawn for irrigation during the preceding season exceeds the amount that is equivalent to a critical depth above the threshold depth of 475 metres. Further, as long as the amount of water that is drawn does not exceed this critical depth, the level of water in the lake would be stable. Following the advice of some hydrologists, this critical depth is defined as the difference between the mean depth of lake water and the threshold depth of 475 metres. The estimation of this critical depth is considered below in section 4.1.4.

4.1.4 Empirical definition of the components of the deterministic linear programming model

OBJECTIVE FUNCTION

Gross margins from cropping

Following Gittinger (1982), the world prices of the appropriate goods and services were nominated as the shadow prices. These prices were defined in constant 1985 values for the estimation of gross margin which is defined as the difference between gross revenue and variable costs. The estimated value of gross margins for the seven crops are presented in Tables 6A to 12A of Appendix V and summarized in Table 4.1 below.

In the Lake Kariba Area, a number of international agencies such as the World Bank, Food and Agriculture Organization, as well

Table 4.1 Gross margins and resource requirements per hectare

	Maize	Cotton	Sunflower	Soyabeans	Sorghum	Rice	Wheat
Gross Margins (Kwacha)	574	294	482	350	312	561	353
Labour (Man-days)	22	42	15	16	37	33	18
Cash Capital (Kwacha)	36	20	10	25	8	14	30
Soil Moisture (mm)	790	640	690	740	550	990	890

Source: Department of Agriculture 1986 and Field Survey 1986 as the Zambian Department of Agriculture and National Research Institutions have calculated gross margins of the crops that are considered in this study. Thus, the gross margins calculated in this study were validated by comparison with the above studies.

The gross margin for each crop is assumed to be the same irrespective of the season or the zone in which it is grown. This is because the Department of Agriculture in Zambia assumes that the production functions for various crops in the Lake Kariba Area differ only according to the crop and not according to the zones or to seasons (Farm Management Annual Reports, 1982-1986). Even studies done by the World Bank (1983) and the Food and Agriculture Organization (1984), in the Lake Kariba Area have differentiated gross margins, and other items such as capital requirements, and crop water requirements only on the basis of crops and not on the basis of zones or the seasons.

Cost of irrigation

The per unit cost of irrigation was estimated by annualizing the investment costs and treating all costs (investment and maintenance costs) as annual costs. For this purpose a discount rate of 5 percent was used. This discount rate of 5 percent is justified on the premise that it is used by the Zambian Government to evaluate its projects. Further, following the information provided by Zambian authorities, it is assumed that the capital investment in the irrigation project has a life span of 50 years. It is also assumed that maintenance costs start being incurred three years after capital investment is completed.

The calculation of the cost of irrigation is illustrated in Table 13A of Appendix VI and is estimated to be 0.14 kwachas per hectare millimetre. Despite differentiating the study area by zones, which in turn are distinguished by separate distances, the estimated irrigation cost of 0.14 kwachas per hectare millimeter of water is used in all the five zones. That is, it is assumed that the cost of using one hectare millimetre of water is the same irrespective of the crop in question and the distance involved. This is because, the area of study is small and thus the differences in irrigation costs between the five zones is negligible. However, the model solution reflects the irrigation costs according to the amount of water required per crop and land use in a given zone.

Cost of credit

Cost of credit refers to the interest rates charged on farmers' loans by official lending institutions. Although such lending institutions are many, e.g. Zambia Agricultural Development Bank, Barclays Bank of Zambia, Standard Bank of Zambia, Development Bank of Zambia and Zambia State Insurance Corporation, small farmers do not have ready access to institutional credit. The issues surrounding limited access to credit are detailed elsewhere (Planning Division Report No.2, 1983 and Economic Reports, 1982 & 1988). The incorporation of credit as a variable in this model would enable the examination of whether ready access to credit has an effect on agricultural production and thereby on drought management.

Although interest rates vary widely in the Zambian economy, herein it is equated to the government bond rate of 5 percent on the premise that the bond rate manifests the social productivity of capital.

MODEL CONSTRAINTS

Land constraint

The land in the study area is divided into 5 zones. This division is based on Scudder's study (1962) which divides the land around Lake

Kariba into various physiographic zones. These five zones are shown in Figure 4.1. The zonal hectarage shown in Table 4.2 below pertains to cultivable land, and has been estimated, (following discussions with authorities in the study area), on the assumption that 40 percent of the land in each zone would be available for crop production. It is assumed that each of the seven crops in the model has an equal chance of competing for available land in each zone.

In Table 4.2, zone 1 has the smallest land area since, much of the land in zone 1 is inundated by water and is hilly. Zone 3 has the largest land area because much of the land in this zone is flat. In zones 4 and 5 land is partly flat and partly rugged because of the escarpment. The net irrigable land of about 162,300 hectares in Table 4.2 conforms to the 162,000 hectares which was recommended for irrigation in the study area in the 1960s (Scudder, 1985).

Labour constraints

Labour requirement and availability are calculated in man-days per hectare per season and according to crop. Total man-days required for a particular crop are dependent on hired labour, on the size of a family and the number of its members available for work on land in a given period and on the number of working days in that period (O'Brien, 1981). Hence, in field surveys carried out in the study area, direct questionnaires were used to elicit the information on labour requirement, and labour availability.

This information was supplemented by other studies conducted in the region (Food and Agriculture Organization, 1984) and was used in the estimation of the coefficients of labour requirement, namely A_{qij}; and labour availability, namely 1_q. The values of labour requirement are presented in Table 4.1 above.

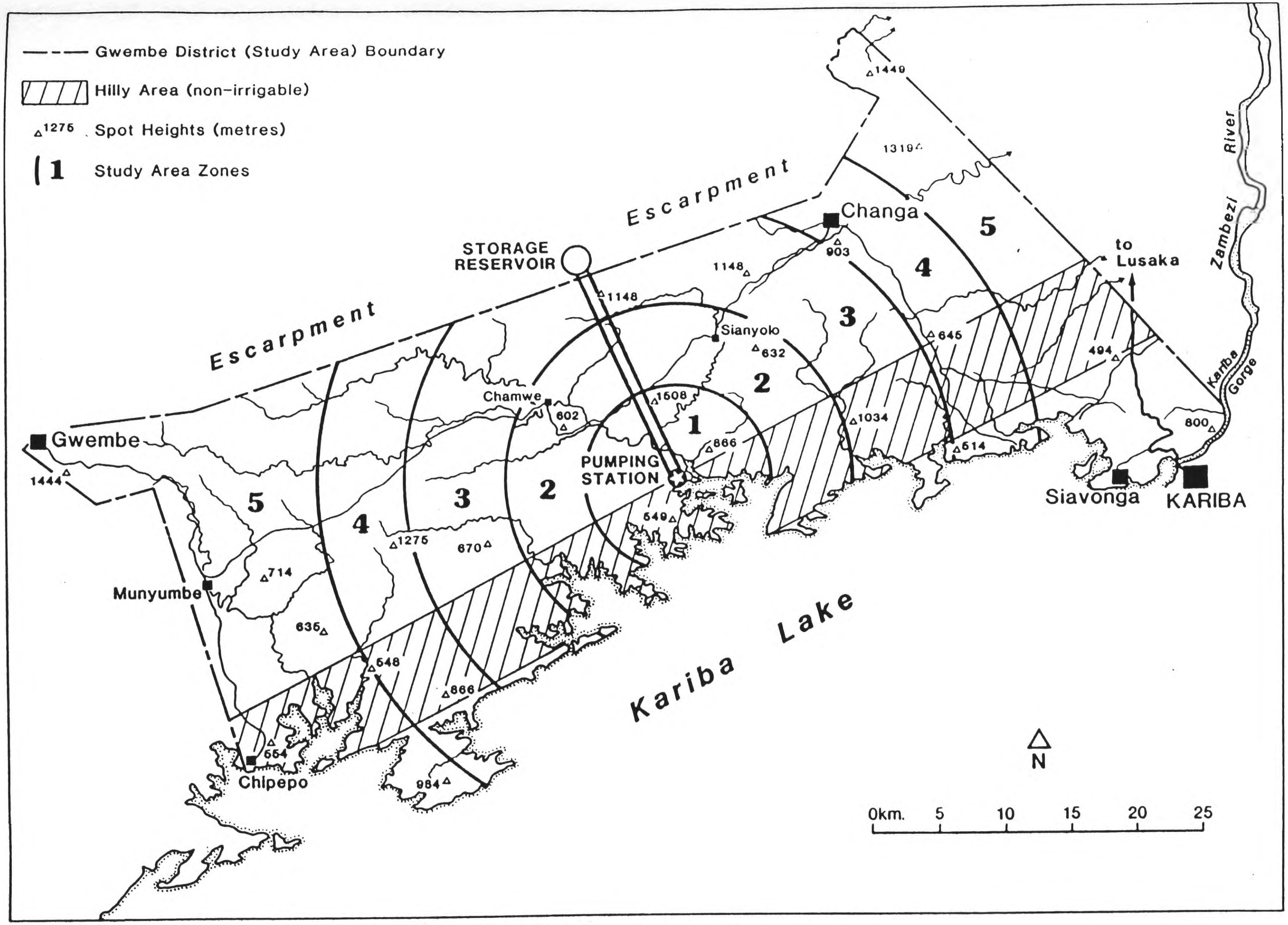


Figure 4.1 The five zones of the study area

Source: Adapted from Scudder (1962).

Table 4.2 Proposed zones of land in the Lake Kariba Area in hectares

Zone	Total Land Area	Net Cultivable Area
1	22,100	13,260
2	53,900	32,340
3	83,100	49,860
4	50,000	30,000
5	61,100	36,600
Total	**270,500**	**162,300**

Source: Department of Agriculture, 1986.

Cash capital

To define this constraint, information on the following items needs to be derived:

(a) amount of cash capital required for a crop;

(b) amount of cash capital that is available at the start of a season; and

(c) farmers' marginal propensity to save.

The information on these items was derived through field surveys. The values of cash capital requirement for the various crops are summarized in Table 4.1 above. The marginal propensity to save was estimated to be thirty percent.

Soil moisture constraint

The soil moisture constraint is defined on the basis of consumptive use for each of the seven crops in the model. These consumptive uses were derived from Nanga National Irrigation Report (1985) and Farm Management Annual Reports (1982, 1986). These values are presented in Table 4.1 above.

It is assumed that a crop requires the same amount of water during both wet and dry seasons irrespective of the place it is planted within Zambia (Nanga National Irrigation Report, 1985). The availability of water for soil moisture is determined by rainfall pattern and water in the lake.

Limit on irrigation constraint

As indicated the inclusion of the limit on irrigation as a separate constraint is to ensure that the depth of the lake does not fall below 475 metres. Hence, the inclusion of this irrigation constraint is to minimize this risk of over utilizing water from Lake Kariba.

Water levels in Lake Kariba have remained stable for a period of 24 years, that is between 1962 and 1986. This stability is illustrated in Figure 4.2 which combines data on water levels for season 1 (November to April) and season 2 (May to October). This stability on lake water levels is also observed on a monthly basis as is illustrated in Figures 6A to 11A in Appendix VIII. The stability of the lake water levels has been attributed to the largeness of the catchment area.

Tables 4.3 and 4.4 show the frequency distribution for Lake Kariba water levels from 1962/63 to 1985/86, for seasons 1 and of 2 respectively. From both of these tables it is observed that the probability that water levels falling below 477 metres is zero. Similarly, the probability that Lake Kariba water levels fall between 481 and 487 metres is eighty-eight percent.

According to the Central African Power Corporation (1986), the average amount of water in Lake Kariba has remained at about 483 metres during the wet and the dry seasons during the years from 1962/63 to 1985/86. Hence, the difference between this average, namely 483 metres and the 475 metres threshold water level is treated as a critical depth. that is, the amount of water available for irrigation is defined by a depth of eight metres above the 475 metre threshold level.

4.2 The stochastic framework for the "with irrigation" option

As with the previous framework, the main components of this framework are also:

(i) a rainfall simulator,

(ii) a Target MOTAD model, and

(iii) the monitor for lake water levels.

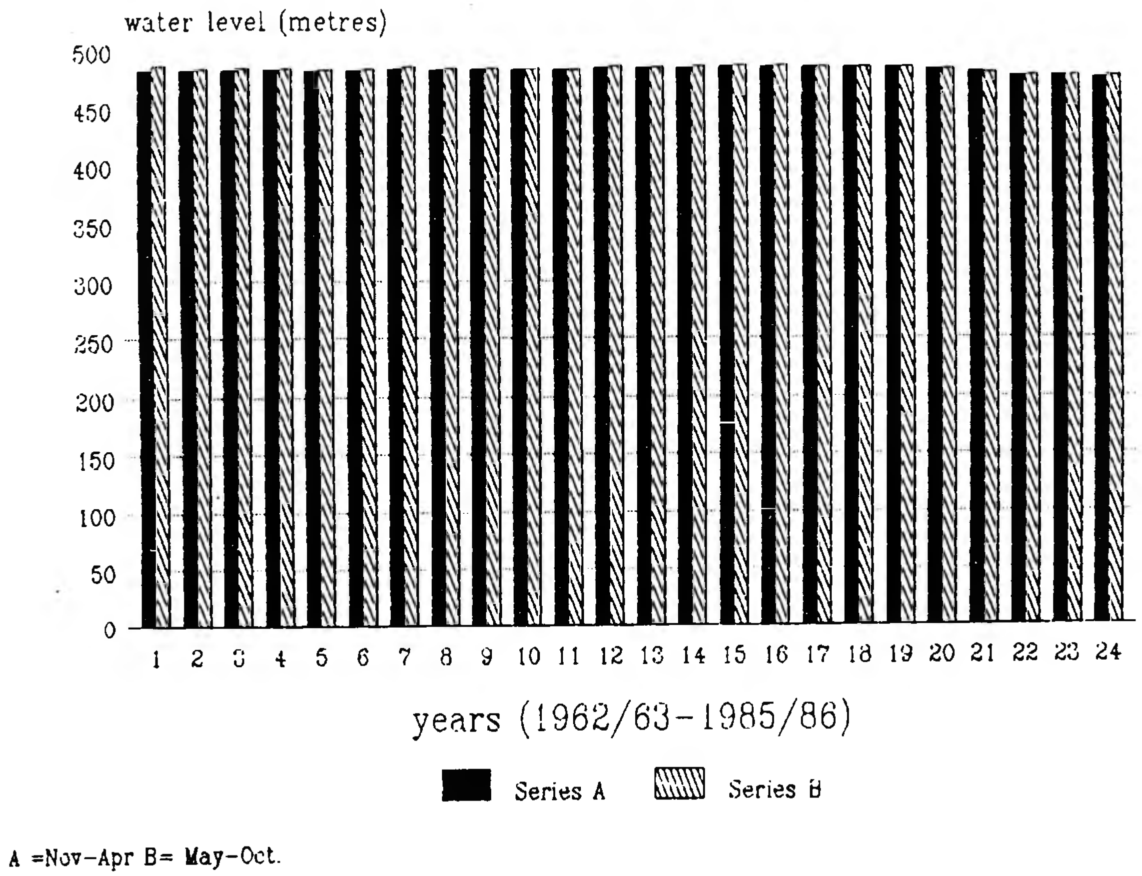


Figure 4.2 Lake Kariba water levels 1962/63 to 1985/86 for November to April and May to October.

Source: CAPCO, Harare (1986) Note: Series A = November to April
Series B = May to October

Table 4.3 Frequency distribution of Lake Kariba water levels for November to April, 1962/63 to 1985/86

Class Limits of Water	Frequency Number of Levels	Percent	Cumulative Frequency Percent
(Metres)			
473 ≤ 475	0	0.00	0.00
475 ≤ 477	0	0.00	0.00
477 ≤ 479	2	8.00	8.00
479 ≤ 481	1	4.00	12.00
481 ≤ 483	6	25.00	37.00
483 ≤ 485	7	29.00	66.00
485 ≤ 487	8	34.00	100.00
	24	**100.00**	

Table 4.4 Frequency distribution of Lake Kariba water levels for May to October, 1962/63 to 1985/86

Class Limits of Water	Frequency Number of Levels	Percent	Cumulative Frequency Percent
(Metres)			
$473 \leq 475$	0	0.00	0.00
$475 \leq 477$	0	0.00	0.00
$477 \leq 479$	2	8.00	8.00
$479 \leq 481$	2	8.00	16.00
$481 \leq 483$	1	4.00	20.00
$483 \leq 485$	9	38.00	58.00
$485 \leq 487$	10	42.00	100.00
	24	**100.00**	

Each of these components are considered in turn.

Since the rainfall simulator and the monitor for lake water levels have been already described in section 4.1 above, the description herein is confined to the second component, namely the Target MOTAD model.

Although a Target MOTAD model is formulated for each season, the components of the Target MOTAD model are the same regardless of the season. As in the previous section, the nature of the components is first described and this is followed by a discussion of the empirical aspects.

4.2.1 The Target MOTAD model

The objective function of the Target MOTAD model concerns the maximization of expected gross margins from the seven crops, namely maize, cotton, sunflower, soyabeans, sorghum, rice and wheat. The constraints pertain to the availability of: land, labour, cash capital, soil moisture, water for irrigation and the cost of risk taking. The last constraint is set within the framework of a decision maker (farmer) wanting to seek a trade-off between: maximizing crop output (and hence revenue) on the one hand, and minimizing the risk of undertaking cropping activities on the other. As indicated previously, the risk is assumed to be caused solely by the uncertainty pertaining to the amount of rainfall.

The description that is offered below follows Tauer (1983). Further discussion on Target MOTAD can be found in Watts, Held and Helmers (1984), Zimet and Spreen (1986) and McCamley and Kliebenstein (1987).

Objective Function

It is assumed that the uncertainty pertaining to the amount of rainfall during a given season influences only the amount of crop output (and hence the gross margins from crops). Hence, expectations are taken only in terms of the gross margins generated from cropping activities. As a result, except for the expected gross margins, $[E\,(C_{qij})\,(X_{qij})]$ the rest of the variables in the objective function of the Target MOTAD model remain the same as those in the deterministic linear programming model. Hence, the objective function is as follows:

$$\text{Maximize } Z = \sum_{q=1}^{5} \sum_{j=1}^{7} [E\,(C_{qij})\,(X_{qij})] - \sum_{q=1}^{5} \sum_{j=1}^{7} K_{qij}\,W_{qij} - \sum_{q=1}^{5} \sum_{j=1}^{7} 1b_{qij}, \tag{4.14}$$

where:

$[E(C_{qij})\,(X_{qij})]$ represents the expected gross margin from crop j that is grown during season i in zone q; and

$q = 1,\ldots,5$

$j = 1,\ldots,7$; and

$i = 1,2.$

The definition of other variables in the objective function follows the same lines as those in seciton 4.1.1.

Constraints

The constraints pertaining to the availability of: land, labour, cash capital, soil moisture and water for irrigation have been already described in section 4.2 above. Hence, the constraints that need to be explained are those pertaining to the cost of risk taking. These are defined as:

(i) negative deviations from a prespecified target revenue; and

(ii) sum of negative deviations multiplied by the probabilities of the states of nature. Herein a state of nature is defined as a particular set of rainfall values during a year. As indicated previously in section 4.1.1 each set consists of these values of rainfall - one for the wet season and the other for the dry season.

The first constraint specifies the following aspect of a decision maker's behaviour as explained by Tauer (1983). That is, whilst wanting to maximize expected income from various activities, decision makers are also concerned about their revenue falling below a critical target. So, the deviations of revenue below a target measures one aspect of the decision makers' risk, and is hence defined as:

$$\sum_{q=1}^{5} \sum_{j=1}^{7} c_{qij} X_{qij} + y_{ik} \geq T_i \tag{4.15}$$

where:

y_{ik} represents deviations below target revenue during season i for the kth state of nature; and T_i represents target revenue during season i.

Following Watts, Held and Helmers (1984) and Hazell and Norton (1986), the second aspect of a decision maker's perception of risk is that the expected value of total deviations below the target over a planning period should be confined to a specific value. To define this aspect of risk perception, Tauer (1983) equates the sum of the product of the probabilities of each state of nature and the deviation associated with the appropriate state of nature. This is specified as:

$$\sum_{k=1}^{s} p_{ik} y_{ik} = \beta \tag{4.16}$$

where:

s represents the number of states of nature, p_{ik} represents the probability of the kth state of nature; and β is a risk parameter which represents the sum of expected negative deviations below target revenue. If β is assigned a value of zero, then it represents a situation where no negative revenue deviations from the target revenue are allowed during any time period. Conversely, when β is assigned a very large number, the model is equivalent to a deterministic linear programming model. It is assumed that when β becomes smaller, decision makers become more risk averse, thus tightening the requirement that target revenue be met (Zimet and Spreen, 1986).

The overall Target MOTAD model specification for a given season is as follows:

$$\text{Maximize } Z = \sum_{q=1}^{5} \sum_{j=1}^{7} [E(C_{qij})(X_{qij})] - \sum_{q=1}^{5} \sum_{j=1}^{7} K_{qij} W_{qij} - \sum_{q=1}^{5} \sum_{j=1}^{7} Ib_{qij}$$

Subject to:

$$\sum_{q=1}^{5} \sum_{j=1}^{7} a_{qij} X_{qij} \leq L_{qi},$$

$$\sum_{q=1}^{5} \sum_{j=1}^{7} A_{qij} X_{qij} \leq 1_{qi},$$

$$\sum_{q=1}^{5} \sum_{j=1}^{7} Q_{qij} X_{qij} - \sum_{q=1}^{5} \sum_{j=1}^{7} b_{qij} \leq M_{qi}$$

$$\sum_{q=1}^{5} \sum_{j=1}^{7} t_{qij} X_{qij} - \sum_{q=1}^{5} \sum_{j=1}^{7} W_{qij} \leq R_{qi}$$

$$\sum_{q=1}^{5} \sum_{j=1}^{7} W_{qij} \leq L_{qi}$$

$$\sum_{q=1}^{5} \sum_{j=1}^{7} C_{qij} X_{qij} + y_{ik} \leq T_i$$

$$\sum_{i=1}^{s} p_{ik} y_{ik} = \beta,$$

$$X_{qij}, b_{qij}, W_{qij}, y_{ik} \geq O \qquad (4.17)$$

4.2.2. Empirical definition of the components of the Target MOTAD Model

Objective function

Since the estimation of the cost of irrigation and the cost of credit have been already discussed above, only the expected gross margin is considered below. Several studies (Rae, 1971a, 1971b; Anderson, Dillon and Hardaker, 1977; and Hazell and Norton, 1986) have suggested using subjective methods in estimating the incomes of decision makers in situations where data is sparse. These methods normally rely on past subjective experiences of decision makers. The above writers argue that decision makers, on the basis of their past experience, know the approximate amount of income to expect should conditions recur which are similar to the ones which occurred in the past. Hence, because of the sparseness of data in the Lake Kariba District, the expected gross margins of this study are estimated by relying on the subjective knowledge of decision makers in the study area. Although this method has several limitations (Anderson, Dillon and Hardaker, 1977) it is the only meaningful one in this situation.

Hence, using this method, the expected gross margins of this study have been estimated for each of the seven crops. The following procedure was used during the field survey stage of this research.

(a) First, farmers and agricultural officers were asked to indicate in millimetres the amount of rainfall they thought constituted a good, medium and bad year for each of the seven crops being dealt with in this study. This understanding of good, medium and bad is based on the crops growing to normal full maturity.

(b) Secondly, farmers were asked to subjectively indicate the gross margin that they would get from each crop for various states of nature (that is, simulated values of rainfall). Their subjective estimates were validated by consultation with agricultural officers in the area. If the subjectively estimated value of gross margin for crop j during season i for state of nature k, is denoted as G_{ijk}; and the probability of the state of nature k during season i, is p_{ik}: then the expected gross margin is $(p_{ik}\,(G_{ijk}))$. The estimation of these expected gross margins for a sample of a few scenarios is illustrated in Appendix VIII. This appendix also includes the probability values that are used for the calculation of expected gross margins.

Constraints

Empirical estimation of the constraints pertaining to the availability of: land, labour, soil moisture, cash capital and water for irrigation have been already explained above. Hence, the discussion here is confined to the constraint on risk taking. The empirical specification of target revenue, was done in consultation with farmers, agricultural experts and policy makers during the field survey. A target revenue of k100 million was arrived at for the region as a whole in each of the two seasons, assuming that irrigation is implemented in the district. The deviations below the target revenue were estimated by subtracting the expected gross margins from the subjectively estimated values of gross margin that are associated with each state of nature. A sample of these deviations is presented in Appendix VIII.

Two methods have normally been used to get the values of the risk parameter (β). The first method which has been used by Tauer (1983) and Zimet and Spreen, (1986) involves the parameterization of the risk parameter (β) from zero to a very large number. The parameterization of β is continued until the model gives the same solution despite increasing the value of β; that is until the model solution does not display any further changes.

The second method which has been used in several studies (Dillon and Scadizzo, 1978; Thampapillai, 1980; Watts, Held and Helmers, 1984; and McCamley and Kliebenstein, 1987), predetermine a fixed value for the risk parameter. This is done either through direct interaction with decision makers or from secondary data. For example, Dillon and Scandizzo, undertook questionnaire surveys among small scale farmers in Northeast Brazil to arrive at the risk value which was used in the quadratic programming model. Thampapillai (1980) used the risk value of 0.5 for the MOTAD model following information obtained from the Australian Bureau of Agricultural Economics.

In this study the value of β is defined as k20 million. The rationalization of this value is based on the premise that the people in the study area in general tolerate losses which amount up to five percent of revenue. Given that the decision makers of the study area have specified a target of k100 million, the amount of risk (losses) that can be permitted is k20 million. For illustrative purposes; the Target

MOTAD model of Zone 1 of the wet season of a selected scenario is presented in Appendix IX.

4.3 The stochastic framework for the "without irrigation" option

The main components of this framework are:

(i) a rainfall simulator; and

(ii) a Target MOTAD model.

Both the rainfall simulator and the Target MOTAD model are already explained above. The Target MOTAD model in the "without irrigation" framework takes a similar form to that of the "with irrigation" framework. However, the difference between the two is that the "without irrigation" model does not have the cost of irrigation in the objective function, and does not have an irrigation constraint. This is because the "without irrigation" option relies entirely on rainfall. Hence, the specification of the model applies to only the wet season.

The overall specification of the Target MOTAD model for the "without irrigation" framework is as follows:

$$\text{Maximize } Z = \sum_{q=1}^{5} \sum_{j=1}^{7} [E(C_{qj})\,(X_{qj})] - \sum_{q=1}^{5} \sum_{j=1}^{7} Ib_{qj},$$

Subject to:

$$\sum_{q=1}^{5} \sum_{j=1}^{7} a_{qj}\, X_{qj} \leq L_q,$$

$$\sum_{q=1}^{5} \sum_{j=1}^{7} A_{qj}\, X_{qj} \leq l_q,$$

$$\sum_{q=1}^{5} \sum_{j=1}^{7} Q_{qj} X_{qj} - \sum_{q=1}^{5} \sum_{j=1}^{7} b_{qj} \leq M_q,$$

$$\sum_{q=1}^{5} \sum_{j=1}^{7} t_{qj} X_{qj} - \sum_{q=1}^{5} \sum_{j=1}^{7} W_{qj} \leq R_q,$$

$$\sum_{q=1}^{5} \sum_{j=1}^{7} C_{qj} X_{qj} y_{qj} \leq T,$$

$$\sum p_1 y_1 = \beta \tag{4.18}$$

Empirical definition of the objective function and of the constraints have been already dealt with above. However, following discussions with farmers and agricultural officers in the study area, a target revenue of k20 million and a risk value of k4 million were used in this Target MOTAD model. The values of the target revenue and the risk parameter are lower in this framework because crop production in the "without irrigation" option is more risky than in the "with irrigation" option.

CHAPTER 5 RESULTS OF THE APPLICATION OF THE FRAMEWORKS

In this chapter the results of the application of the three frameworks that were described in the previous chapter are presented. The application of each framework was repeated for each of the thirty scenarios that were previously identified. As indicated in chapter 4, thirty scenarios were randomly generated using a rainfall simulator, where each scenario represents a sequence of rainfall patterns over a six year period. That is, each scenario contains six sets of rainfall values with each set representing two rainfall values: one for the wet season and the other for the dry season. Hence wherever possible, the results, for example, for the first year of the planning period were elicited by taking the average of the thirty values pertaining to the first year across the thirty applications.

With the framework involving stochastic models, each set or pair of rainfall values within a scenario was defined as a state of nature. That is, each application of the stochastic model entails six states of nature which enables the identification of variability in output over the six year planning period. This facilitates the recognition of the premise that the aim in applying the stochastic models is to maximize revenue from output as well as minimize the risks of incurring revenue losses over the six year planning period.

5.1 Results of the application of the frameworks for the "with irrigation" option.

5.1.1 The deterministic framework application

Results of the framework applications involving the deterministic linear programming model for the "with irrigation" option are summarized for the wet and dry seasons in Tables 5.1 and 5.2 respectively. The results of both tables are presented on an annual basis for a six year planning period. Of the four items reported in each table, three items, namely irrigation water requirement, credit requirement and net revenue have also been estimated as average values across the thirty scenarios for the appropriate year.

In all scenarios, the maximum amount of land available in all zones was allocated exclusively for the production of maize in both seasons. Consider first the results for the wet season (Table 5.1). The model selects maize as the most profitable crop, and the entire land area of 162,244 hectares is allocated to the production of maize. The variation of gross margins in (column five) is due to variation in irrigation crop water requirements. The crop water requirements vary according to the prevailing states of nature (rainfall). That is, if rainfall is adequate for a particular crop, then the need for irrigation is nonexistent, and the cost of irrigation would not be incurred. In such a context, credit requirement which represents the amount of funds needed to finance irrigation activities would decrease. From the results of Table 5.1 it is observed that on average 38 million hectare millimetres of irrigation water, and k5.4 million of cash credit are required per season each year. The average gross margin generated per season each year is k88 million. This is far greater than the annual net revenue generated at present under rainfed conditions and is even

Table 5.1 Summarized results of the deterministic linear programming model in the wet season's "with irrigation" strategy.

Plan Year	Land Allocation (ha) Maize	Irrigation Water Required (000)hamm Maize	Credit Required (000)kwacha Maize	Gross Margin (000)kwacha Maize
1	162,244	38,300	5,646	87,800
2	"	39,941	6,100	87,100
3	"	39,941	6,100	87,100
4	"	37,520	4,668	88,000
5	"	38,100	5,452	87,600
6	"	35,400	4,326	90,900
Total		**229,202**	**32,292**	**528,500**
Average (per season)		**38,200**	**5,382**	**88,083**

Summarized from 30 scenarios of the wet season's "with irrigation" deterministic linear programming model solutions.

Table 5.2 Summarized results of the deterministic linear programming model in the dry season's "with irrigation" framework.

Plan Year	Land Allocation (ha) Maize	Irrigation Water Required (000)hamm Maize	Credit Required (000)kwacha Maize	Gross Margins (000)kwacha Maize
1	162,244	123,792	5,841	75,134
2	"	122,332	5,841	75,425
3	"	126,713	5,841	74,716
4	"	123,792	5,841	75,134
5	"	125,252	5,841	74,925
6	"	128,173	5,841	74,507
Total		**750,054**	**35,046**	**449,841**
Average (per season)		**125,009**	**5,841**	**74,974**

Summarized from 30 scenarios of the dry season's "with irrigation" deterministic linear programming model solutions.

significantly greater than the cumulative revenue generated under present conditions over the period 1976 to 1985.

Results in Table 5.2 are similar to those of Table 5.1. During the dry season the seasonal average gross margin is approximately k75 million, and the requirements of irrigation water and credit amount to 125 million hectare millimetres and cash capital of k5.8 million respectively. As with the wet season the model solution dictates the allocation of the entire land in the district for the production of maize. From Table 5.2 it is also observed that gross margins remain stable over the six year planning period. This is because there is less variation in irrigation water requirements during the dry season as hardly any rainfall occurs during the dry season. The comparison of Tables 5.1 and 5.2 shows differences in the gross margins, irrigation water and credit requirements. These differences are caused by the stochastic nature of rainfall which in turn influences the amount of irrigation water and credit required for the "with irrigation" option. As indicated, the results of Tables 5.1 and 5.2 show that the optimal cropping pattern is to allocate the entire 162,244 hectares of land to the production of maize. However, the existing cropping pattern is based on crop diversification. Further, decision makers have recommended crop diversification even under an irrigation strategy (World Bank 1983 and Economic Report, 1986). Hence, the results of these tables seem not to conform to existing and the anticipated future farming practices in the area.

Moreover, the above results do not incorporate the following policy goals that have been proposed by the government regarding cotton and sorghum production in the area (Department of Agriculture, 1986). These policy goals are as follows.

(a) The study area should produce at least 13,000 tons of cotton to meet the cotton ginnery requirements in the area. This policy goal is equivalent to allocating at least 19,500 hectares of land for the cultivation of cotton (Lint Company, 1985).

(b) Since sorghum in the study area is a current staple food crop, the government would like the area to produce at least 40,000 tons of sorghum to meet the food requirements. This is equivalent to allocating 30,000 hectares for sorghum (Department of Agriculture, 1986).

The models were solved separately with each of these policy goals included as single policy goal constraints as well as joint policy goal constraints. This enabled the impact of these policy goals to be quantified.

The results of the model solutions that include these policy goals are reported in Table 5.3. According to results of Table 5.3, k88 million is realized from 162,244 hectares of land in the wet season, if no policy goals are included in the deterministic linear programming model. The introduction of the first policy goal in the wet season, namely that at least 19,500 hectares of cotton be grown, reduces the gross margin from k88 million to k77 million. Thus, the value of the first policy goal in the wet season can be defined by the reduction in gross margin, that is k11 million. Incorporating the second policy goal in the wet season, namely that at least 30,000 hectares of sorghum must be grown reduces the gross margin from k88 million to k72 million. Hence, the value of the second policy goal can be equated to k(88-72) million = k16 million. Further, as shown in Table 5.3, the incorporation of first and second policy goals together reduces the gross margin by k27 million to k61 million. The results of including

Table 5.3 Comparison of summarized results of the deterministic linear programming model in the "with irrigation" framework incorporating policy goals one and two.

	Wet Season Land Allocation				Dry Season Land Allocation			
Policy Goals Number	Maize (ha)	Cotton (ha)	Sorghum (ha)	Gross Margin (k million)	Maize (ha)	Cotton (ha)	Sorghum (ha)	Gross Margin (k million)
0	162,000	0	0	88	162,000	0	0	75
1	142,744	19,500	0	77	142,744	19,500	0	66
2	132,244	0	30,000	72	132,244	0	30,000	61
1 + 2	112,700	19,500	30,000	61	112,700	19,500	30,000	52

NOTE:

Policy goal 1: At least 19,500 hectares of land must be allocated to cotton.

Policy goal 2: At least 30,000 hectares of land must be allocated to sorghum.

these policy goals in the dry season are similar in that gross margin falls from k75 million to: k66 million with the first policy goal; k61 million with the second policy goal; and k52 million with both policy goals. Thus, the value of the first policy goal is k9 million compared to the value of second policy goal of k14 million.

Despite the reduction in gross margin by incorporating the policy goals in the model, gross margin realized from the dry and the wet seasons of the solutions from this model are much higher than even the cumulative revenue earned during the ten years from 1976 to 1985. To recapitulate, under present conditions, average annual per capita income is k181 and the average annual regional income is k15 million (see Table 3.2 in Chapter 3).

5.1.2 The stochastic framework application

Results of the stochastic framework for the "with irrigation" option in the wet and dry seasons are presented in Table 5.4. The results reported in this table were derived as follows.

As indicated in chapter 4, the Target MOTAD model was formulated with the target revenue of k100 million and risk parameter β specified as k20 million. The Target MOTAD model was then applied across the thirty scenarios that were previously identified in both seasons without any policy goals. A simple average was taken from the results obtained from the solution of these thirty scenarios. These average values are reported in the first row of Table 5.4. The Target MOTAD model was then solved with the policy goals that were used in the deterministic framework, namely that at least 19,500 hectares of cotton and 30,000 hectares of sorghum must be grown.

Table 5.4 **Comparison of summarized results of the stochastic model (Target MOTAD) of the "with irrigation" option during the wet and dry seasons at risk value of k20 million and target revenue of k100 million.**

	Wet Season Land Allocation				Dry Season Land Allocation			
Policy Goals Number	Maize (ha)	Cotton (ha)	Sorghum (ha)	Gross Margin (k million)	Maize (ha)	Cotton (ha)	Sorghum (ha)	Gross Margin (k million)
0	4,706	157,538	0	85	4,706	157,538	0	72
1	37,046	125,198	0	79	37,046	125,198	0	63
2	0	132,244	30,000	70	0	132,244	30,000	51
1 + 2	4,500	127,744	30,000	65	4,500	127,744	30,000	42

The results of incorporating these additional policy goals are shown in the remaining three rows of Table 5.4.

This table also shows a comparison of the results of the wet and dry seasons. As can be seen from the first row of this table, crop diversification is dictated even without the policy goals being introduced in the stochastic model. Further the model solution presents the same pattern of diversified cropping involving maize and cotton for both the wet and dry seasons. The expected gross margin that is earned during the wet season exceeds that of the dry season by k13 million. As expected this is due to the extra irrigation that is required during the dry season. The incorporation of the first policy goal in the stochastic model, namely that at least 19,500 hectares of cotton be grown, results in a reduction in gross margin by k6 million for the wet season and by k9 million for the dry season. When the second goal is incorporated, namely that at least 30,000 hectares of sorghum must be grown, the reduction in gross margin amounts to k9 million in the wet season and k12 million in the dry season. The joint consideration of the policy goals results in the reduction of k15 million for the wet season and k21 million for the dry season.

5.1.3 Evaluation of the results for the "with irrigation" option.

According to the results of the deterministic framework which are reported in Tables 5.1, 5.2 and 5.3, specialization in the production of maize is preferred. On the other hand, the results of the stochastic framework recommend crop diversification. Furthermore, through crop specialization, that is by growing maize as the only crop, the region would earn k3 million more than if crop diversification were adopted. Despite the higher revenue generated by crop specialization, the results of the stochastic framework are preferred in this study. This is because the stochastic framework represents reality more adequately than the deterministic framework. This choice is further supported by:

(i) the fact that farmers in the Lake Kariba District are risk averse; and

(ii) there is evidence to support that while crop diversification portrays farmers' aversion to risk, specialization in one crop implies farmers' neutrality to risk (Heady, 1952; Dillon and Anderson, 1971 and Hazell and Scandizzo, 1977).

The difference in gross margins between the two model solutions can be defined as the value that society places on adopting a strategy that minimizes risk.

Although the stochastic framework seems to be more realistic than the deterministic framework, its formulation involved the empirical estimation of certain coefficients with limited data. Examples of such coefficients are the per unit cost of irrigation and credit. It is hence, possible that changes in the value of these coefficients can result in significant changes in the results that were described above. Therefore, it is pertinent to undertake sensitivity analyses to test the validity of the results that were derived from the stochastic framework. When it is found that the value of certain coefficients (that may have been erroneously estimated) may change over wide ranges without affecting the results, then errors in estimation need not be a source of concern. If the reverse is true, then one needs to exercise care in interpreting the results of the model.

In this study three sets of sensitivity analyses were performed. These are sensitivity analyses pertaining to: the objective function, the right hand side of the constraint limiting the use of irrigation water, and the risk parameter (β).

Given that the pattern of resource allocation that was prescribed by the framework application was similar for both the wet and dry seasons, the sensitivity analyses are confined to the components of the framework that concern the wet season.

SENSITIVITY ANALYSIS PERTAINING TO THE OBJECTIVE FUNCTION

The coefficients that were tested in the objective function were the cost of irrigation and the cost of credit. The computations in each of these sensitivity analyses is explained below.

Cost of irrigation

To recapitulate the component of the objective function that deals with the cost of irrigation is,

$$\sum_{q=1}^{5} \sum_{j=1}^{7} k_{qij} W_{qij}$$

Where k_{qij} and W_{qij} represent respectively the cost of irrigation per hectare millimetre and the amount of irrigation. The value of k_{qij} was estimated in chapter 4 as k0.14 hectare millimetre of water. However, given that the estimate of (k_{qij}) was performed using sparse data, it is pertinent to examine the sensitivity of the results to changes in k_{qij}. Hence, sensitivity analysis of the cost of irrigation per hectare millimetre of water was done by varying the value of k_{qij} from k0.14 to k20. Values smaller than k0.14 were not considered because of the widespread belief among decision makers that the cost of irrigation can only increase and not decrease. The summary of results from this sensitivity analysis is reported in Table 5.5 and Figure 5.1. This summary is drawn from the model solutions of the Target MOTAD model which was applied to the thirty scenarios for the wet season.

Increases in the cost of irrigation result in changes in the patterns of resource allocation. Initial increases from k0.14 to k0.28 favour an increase in maize production and a reduction in cotton production. However, further increases in the cost of irrigation beyond k0.28 favour increases in the production of cotton and sorghum at the expense of maize. As expected the size of gross margins falls as the cost of irrigation increases.

The solution also reveals variability; for example, as cost of irrigation increase the amount of maize initially decreases, then increases and finally decreases. This is due to the process of averaging across thirty scenarios which depict widely different sequences of rainfall. Despite this variability, the overall tendency is that as cost of irrigation increases maize production declines and production in sorghum becomes dominant. This is due to the fact that sorghum has the lowest consumptive use for water. The model solution in terms of land use is insensitive to increases in the cost of irrigation beyond k6 per hectare millimetre of water.

Table 5.5 **Summarized results of sensitivity analysis for cost of irrigation per unit quantity of irrigation water.**

Cost of Irrigation K_{qij}	Land Allocation Maize	Cotton	Sunflower	Sorghum	Gross Margin
(kwacha)	(ha)	(ha)	(ha)	(ha)	(k million)
0.14	4,706	157,538	0	0	85.0
0.28	37,046	125,198	0	0	82.5
1.00	0	129,904	0	32,340	69.4
2.00	0	125,663	0	36,340	58.7
4.00	0	0	13,260	148,984	47
6.00	0	2,244		160,000	41
8.00	0	0	0	160,000	38
10.00	0	0	0	160,000	35
20.00	0	0	0	160,000	17

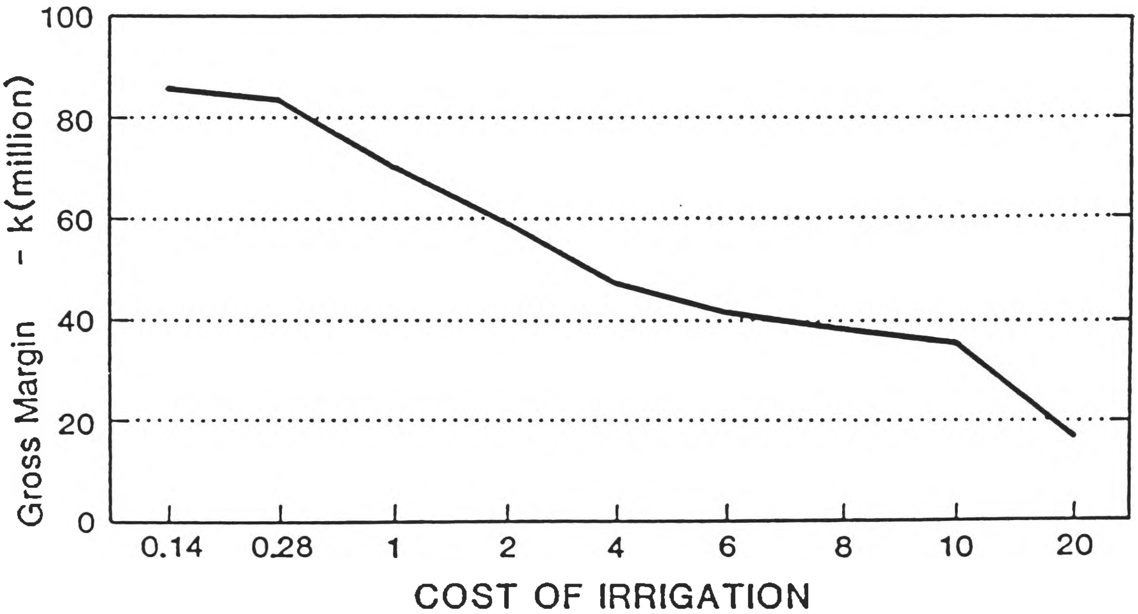


Figure 5.1 Sensitivity analysis of cost of irrigation to gross margin

Cost of credit (interest rates)

The cost of credit (interest rate) fluctuates widely in Zambia. The results presented above were based on an interest rate of five percent. However, some Zambian decision makers indicate that it is plausible for private money lenders to charge interest rates as high as eighty per cent. For example, Lele (1975) has noted that noninstitutional interest rates can be as high as 110% in certain African countries. Hence, the sensitivity of the results to varying interest rates between five percent to eighty per cent was tested, and the results of these tests are reported in Table 5.6 and Figure 5.2. It is shown that the results of the stochastic framework are sensitive to variation in interest rates charges.

As with the cost of irrigation, an initial increase in the cost of credit up to ten per cent results in an increase in the production of maize at the expense of cotton. However, increases in interest rates beyond ten per cent prompt an increase in the production of cotton at the expense of maize. However, the model solution is insensitive in terms of land use to further increases in interest rates beyond thirty percent. That is, land is allocated between cotton and maize and the amount of land allocated remains unchanged. However, despite constant land being allocated to these two crops, the revenue obtained from these crops shows a continuous but small decrease. This is because as interest rates increase, more funds are required to pay for the loans. The "with irrigation" model was also solved by excluding the credit facility. Hence, in this test, the objective function was written as:

Table 5.6 Summarized results of sensitivity analysis for cost of credit

Cost of Credit	Land Allocation		
Ibqij (percent)	Maize (ha)	Cotton (ha)	Gross Margin (k million)
0.05	4,706	157,538	85.0
0.10	37,046	125,198	84.9
0.15	30,046	131,168	84.7
0.30	28,456	133,788	84.3
0.50	37,046	125,198	83.7
0.60	37,046	125,198	83.4
0.80	37,046	125,198	82.9

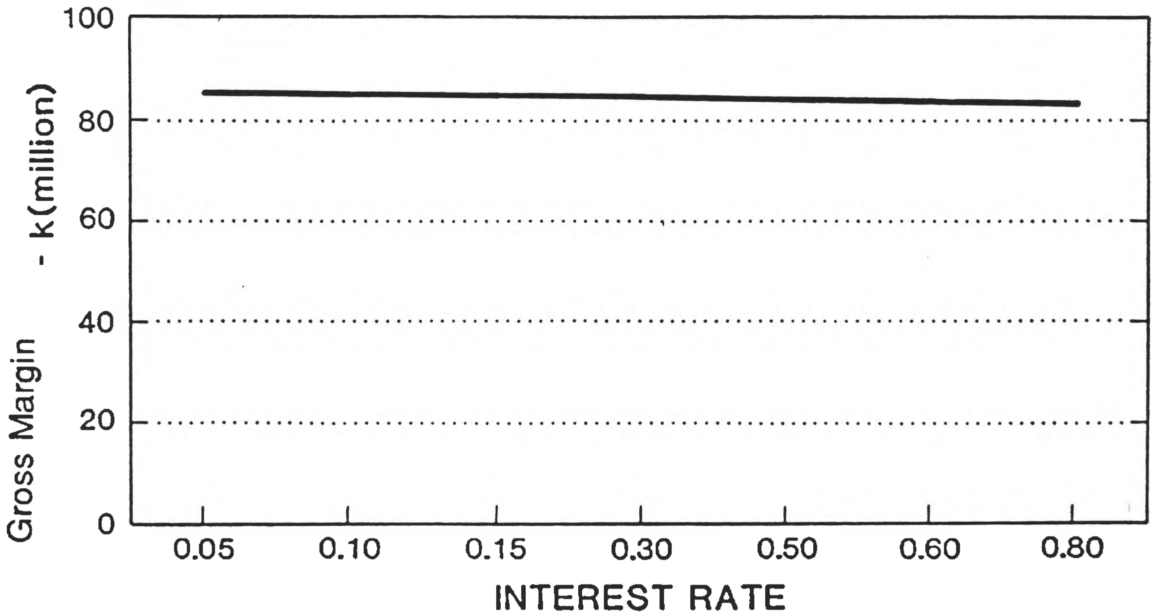


Figure 5.2 Sensitivity analysis of interest rates to gross margin

$$\text{Maximize } Z = \sum_{q=1}^{5} \sum_{j=1}^{7} [E(c_{qij})(X_{qij})] - \sum_{q=1}^{5} \sum_{j=1}^{7} k_{qij}W_{qij}.$$

That is, the cost of credit $\left[\sum_{q=1}^{5} \sum_{j=1}^{7} Ib_{qij} \right]$ was removed and the objective function was maximized in terms of the expected gross margins net of only the cost of irrigation. The redefinition of the objective function had to be also accompanied by a redefinition of the cash capital constraint as:

$$\sum_{q=1}^{5} \sum_{j=1}^{7} Q_{qij}X_{qij} \leq M_{qi}.$$

That is, the credit variable (b_{qij}) was also removed from the cash capital constraint and hence, the constraint now meant that the cash capital requirement of the various crops cannot exceed the amount of capital that the farmers possess. The result of this application highlighted the relative importance of a credit policy, since, as expected, the gross margin declined. The model solution also dictated the allocation of land to the cultivation of only cotton, and the extent of this cultivation was 47,000 hectares. Hence, the withdrawal of the credit facility, in the context of the "with irrigation" option, results in a significant drop in the expected gross margin. This drop is approximately k60 million.

Sensitivity analysis on the size of the irrigation constraint

This constraint limits the use of water from the dam to quantities that fall within the limits that are specified by the Kariba Dam Authority, namely, the Central African Power Corporation (CAPCO).

As already outlined in Chapter 4, CAPCO has placed the limit that the depth of lake water must be maintained at 475 metres for the generation of hydroelectricity for Zambia and Zimbabwe. That is, the irrigation constraint specifies that the amount of water demanded by various crops in the model should be less than or equal to the amount of surplus water that lies above the depth of 475 metres of water. This surplus water was defined on an average basis as a depth of eight metres. Hence, the sensitivity analysis was performed by successively reducing this depth of eight metres up to a depth of zero. That is, a depth of zero for surplus water implies that the depth of the lake is 475 metres and at this depth of water, no water is available for irrigation.

The results of sensitivity analysis are presented in Table 5.7. The results in this table indicate that when no water is available for irrigation, the only crop that can be grown is sorghum. This is expected because of the seven crops considered, sorghum has the lowest consumptive use of water. Cotton and maize replace sorghum as the available water increases. When this happens gross margin increases significantly. The persistence of cotton in the model solution indicates that cotton can be perceived as a stable source of income in the Lake Kariba District. Further, any increase in the amount of water that is available for irrigation above a depth of one metre, leaves gross margin and land allocation between maize and cotton at constant values.

Figure 5.3 shows the relationship between the depth of water allowed for irrigation above the threshold level of 475 metres and gross margin. According to this figure, gross margin is sensitive to variation in water levels of between zero and one. However, it stabilizes at a constant level from the depth of water one metre and onwards.

Table 5.7 Summarized results of sensitivity analysis for Lake Kariba water levels from 475 metres threshold level to above this number using stochastic model (Target MOTAD)

	Land Allocation			Gross Margin
Water Level (metres)	Maize (ha)	Cotton (ha)	Sorghum (ha)	K Million
0	0	0	36,600	12
0.002	0	0	127,509	40
0.01	0	81,483	80,761	69
0.02	0	77,700	105,444	74
0.9	0	39,000	121,031	77
1.0	4,706	157,538	0	85
2.1	4,706	157,538	0	85
4.0	4,706	157,538	0	85
10.0+	4,706	157,538	0	85

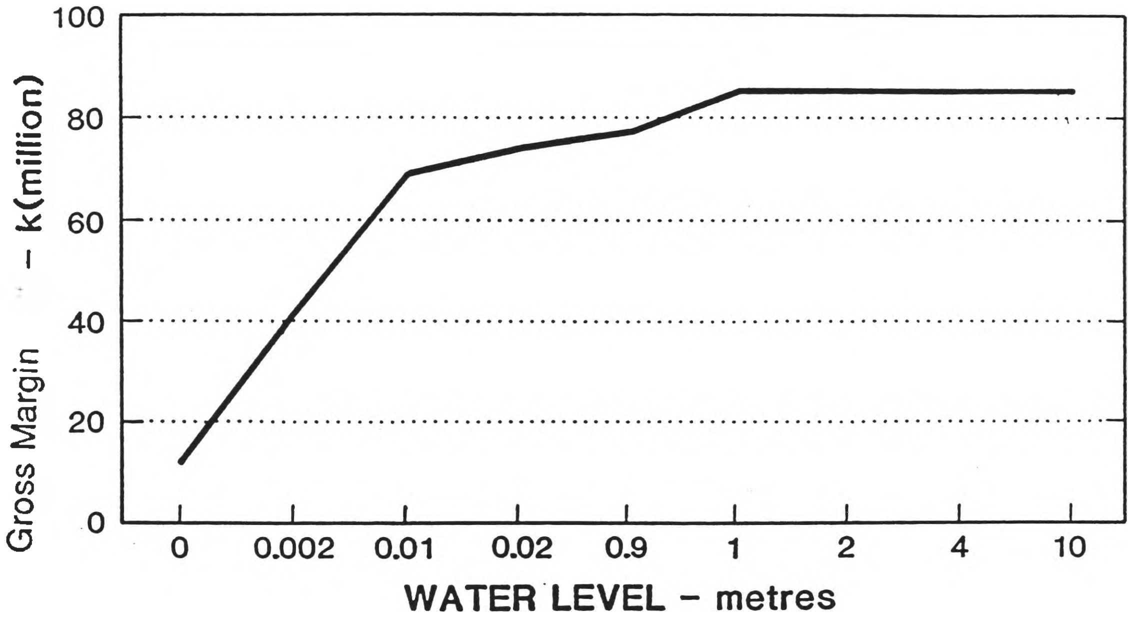


Figure 5.3 Sensitivity analysis of water levels and gross margin.

Sensitivity analysis on the risk parameter β

Recall that in this study, for reasons given in Chapter 4, the risk parameter (β) was fixed at k20 million and the target revenue was fixed at k100 million. Following the detailed surveys conducted in the area, the values of k100 million for target revenue can be regarded as a reasonable certain estimate. However, the size of the risk parameter β was based on the assumption that farmers in the district are willing to tolerate losses of approximately twenty per cent of revenue. The sensitivity of the results to changes in this assumption was tested by changing the value of β as indicated in Table 5.8 and Figure 5.4.

The results in Table 5.8 indicate that as β increases from zero to k50 million both expected gross margin and cropping patterns remain the same as those obtained from the results of the Target MOTAD model solution which are presented in Table 5.4. However, when the value of β is increased from k50 million to k60 million, expected gross margin increases by k2 million, and there is a change in the allocation of land between cotton and maize. The amount of land allocated to cotton decreases while that allocated to maize increases. This may be explained by the fact maize is generally perceived as a high value crop. This is consistent with results that were derived from the deterministic framework in that profit was maximized by allocating all available land to the production of maize. Further, Table 5.8 and Figure 5.4 also reveal that the model solution is insensitive to increases in the value of β beyond k60 million.

Recall that a value of zero for β implies complete risk aversion, whilst higher values for β imply risk-taking behaviour. However, the general conclusion that can be drawn from the results of Table 5.8 and Figure 5.4 is that the Target MOTAD model solution in the "with

Table 5.8 Summarized results for sensitivity analysis for the risk parameter (β) for the stochastic model in the "with irrigation" framework at target revenue of k100 million in the wet season

Risk Parameter β (k million)	Policy Goals (Number)	Land Allocation to Crops (in hectares)			Expected Gross Margin
		Maize	Cotton	Sorghum	K Million
0	0	4,706	157,538	0	85
10	1	37,046	125,198	0	79
10	2	0	132,244	30,000	70
10	1+2	4,500	127,744	30,000	65
20	1	37,046	125,198	0	79
20	2	0	132,244	30,000	70
20	1 + 2	4,500	127,744	30,000	65
50	1	37,046	125,198	0	79
50	2	0	132,244	30,000	70
50	1 + 2	4,500	127,744	30,000	65
60	1	44,516	117,728	0	81
60	2	4,706	127,538	30,000	72
60	1 + 2	2,141	130,103	30,000	67
90	1	44,516	117,728	0	81
90	2	4,706	127,538	30,000	72
90	1 + 2	2,141	130,103	30,000	67

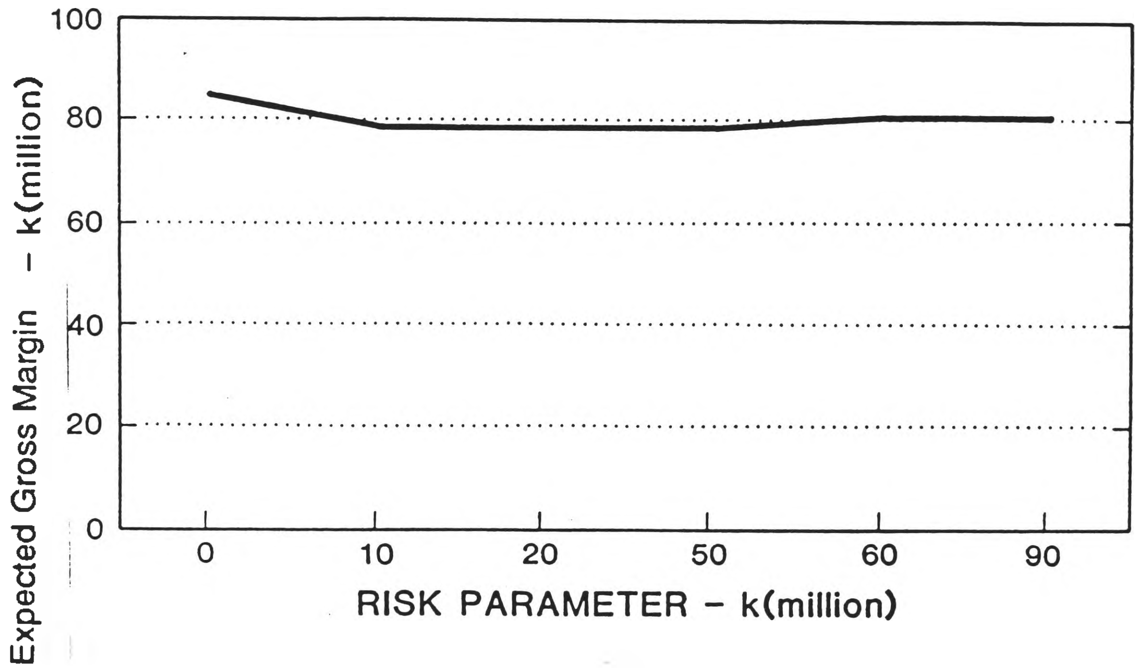


Figure 5.4 Risk parameter (β) of the "with irrigation" option and gross margin.

irrigation" framework is insensitive to variability in the values of β. This can be explained by the fact that the availability of water for irrigation negates the effects of risk perception.

5.2 Results of the application of the framework for the "without irrigation" option.

To recapitulate, the Target MOTAD model which was used in this context had target revenue and the risk parameter specified as k20 million and k4 million respectively. The specification of a substantially smaller target revenue (relative to that of the "with irrigation" option) follows the anticipation that crop yields would be much lower without irrigation. As with the other cases considered above, this model was also applied across the thirty scenarios that were identified previously.

5.2.1 Discussion of the results

Results of the "without irrigation" option are presented in Table 5.9. From the results of this table the following inferences can be drawn, namely that:

(i) a new cropping pattern is suggested;

(ii) the change in cropping pattern coincides with government plans to introduce new crops in the area; and

(iii) the policy goals are infeasible.

A brief discussion for each of the above inferences is given below.

Recall from Chapter 3 that the existing patterns of resource allocation generate an income of approximately k15 million (see Table 3.2). The results of Table 5.9 show that for income to rise from the existing level of k15 million to the expected level of k18 million as

Table 5.9 Summarized results of the stochastic model (Target MOTAD) in the "without irrigation" framework at target revenue of k20 million.

Risk Parameter β (k million)	Policy Goals (Number)	Land Allocation to Crops (in hectares)			Expected Gross Margin
		Sorghum	Rice	Soyabeans	K Million
4	0	45,614	30,070	43,570	18
4	1	—	—	—	Solution infeasible
4	2	45,614	30,070	43,570	18
4	1 + 2	—	—	—	Solution infeasible

observed in Table 5.9, a new cropping pattern is required in the Lake Kariba District. This means that the existing cropping pattern of sorghum, cotton, sunflower and maize should be replaced by the cropping pattern which relies on sorghum, rice and soyabeans.

The government's long - term plan is to introduce in the Lake Kariba District, the production of soyabeans, rice and wheat into the existing cropping pattern of sorghum, maize, cotton and sunflower in the Lake Kariba District (World Bank, 1983; Department of Agriculture, 1986). The validity and rationale of such a long-term plan is not examined here. Hence, in this thesis the above long-term plan is taken for granted. The implication of the results of Table 5.9 is that the optimal cropping pattern is to grow sorghum, rice and soyabeans and leave out the other four crops, namely cotton, sunflower, maize and wheat. The opportunity cost of adopting the government's long-term plan is valued as k3 million. This represents the difference in revenue between the existing cropping pattern (Table 3.2) and the cropping pattern as observed in Table 5.9.

As mentioned above the government has stated two policy goals, namely that at least 19,500 hectares of land should be allocated to the production of cotton and 30,000 hectares of land should be allocated to the production of sorghum. Just as these policy goals are incorporated in the deterministic linear and Target MOTAD programming models of the "with irrigation" framework, they are also included in the Target MOTAD model of the "without irrigation" framework. However, when the first policy goal, was introduced in the model, the model solution became infeasible. The infeasibility of the model solution can be explained by the stochastic nature of rainfall in the Lake Kariba District which normally falls below the mean average minimum in most of the time periods (see chapter 3, section 3.1). This means that the introduction of cotton in the cropping pattern would demand the sharing of the already depleted soil moisture among rice, sorghum and soyabeans.

The second policy goal, namely that 30,000 hectares of land should be allocated to sorghum, is satisfied without any difficulty. However, when the first and the second policy goals were simultaneously introduced into the model the model solution became infeasible. This infeasibility is caused by the inability to meet the moisture requirements for cotton.

5.2.2 Sensitivity Analysis

It would be also relevant to test the sensitivity of the results of this model. Given that the model is applied in the context of "without irrigation" the items that were considered are: credit and the risk parameter (β). These are dealt with below.

Credit

Unlike in the application of the "with irrigation" option, the results of the "without irrigation" framework were far more sensitive to changes in the cost of credit. As shown in Table 5.10 and Figure 5.5, increases in the cost of credit were accompanied by decreases in the expected gross margin, and changes in the pattern of resource allocation. That is, more land was allocated to sorghum as cost of credit increases.

The importance of the credit facility was also tested like before, (Section 5.1.3) by removing the credit variable from the objective function and the cash capital constraint. The solution of the Target

Table 5.10 Summarized results of sensitivity analysis for cost of credit in the "without irrigation" framework

Cost of Credit	Land Allocation			Gross Margin
Ib_{qij} (percemt)	Sorghum	Soyabeans	Rice	K million
0.05	45,614	43,570	30,070	18.2
0.10	50,857	50,857	0	18.0
0.15	50,857	50,857	0	18.0
0.30	54,750	48,614	0	17.8
0.50	55,131	46,504	0	17.5
0.60	60,605	44,504	0	16.9
0.80	62,352	40,006	0	15.8

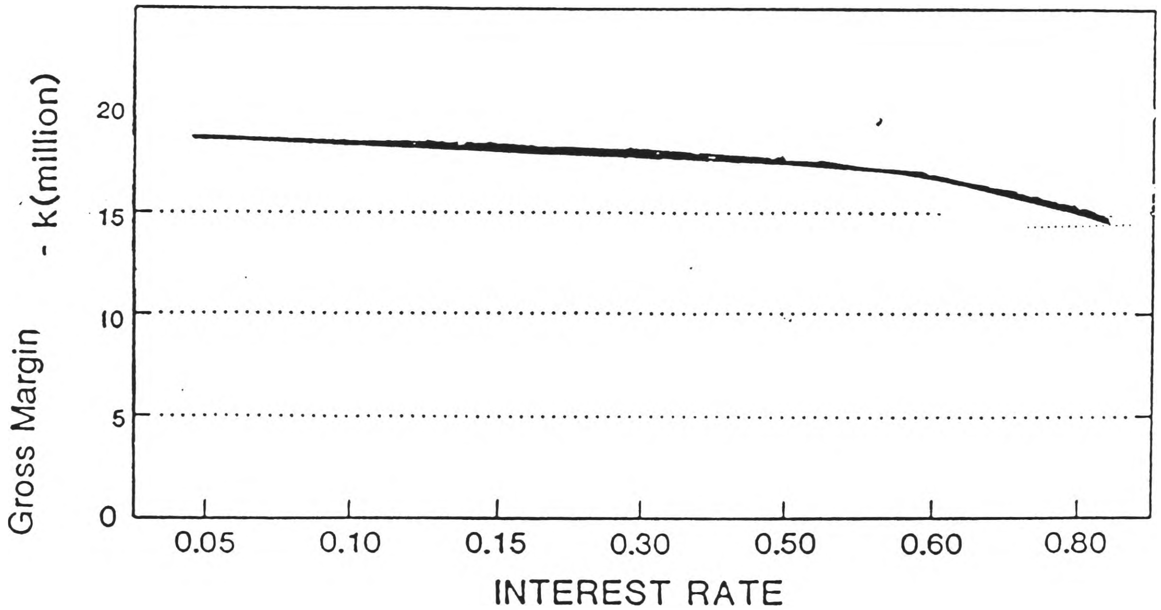


Figure 5.5 Sensitivity analysis of cost of credit to gross margin in the "without irrigation" framework

MOTAD model dictated the allocation of 80,000 hectares of land to grow only sorghum and the value of the expected gross margin amounts to k9.2 million. Given that the size of the expected gross margin in the "without irrigation" context, when credit is available, is k18 million, the removal of the credit facility results in a halving of the gross margin.

The risk parameter (β)

The Target MOTAD model which was applied to the "without irrigation" framework was specified to have a fixed risk value (β) of k4 million and a target revenue of k20 million. This is because decision makers in the Lake Kariba District are assumed to tolerate losses amounting to one fifth of the target revenue. As indicated previously (section 5.2) there could be some concern regarding the assumption about β. Hence, the risk value of k4 million was varied from zero to k16 million in order to test the sensitivity of the model to changes in β. The results of this sensitivity analysis are presented in Table 5.11 and Figure 5.6.

According to this table and figure, expected gross margin rises initially when β increases from zero to k4 million. Then it remains the same until it reaches k10 million. However, there is a slight increase in revenue when β increases further from k10 million to k16 million. As this increase in revenue takes place, the cropping pattern changes from diversified cropping of rice, sorghum and soyabeans to the specialization in the production of sorghum. This specialization in sorghum, despite it being a low valued crop, occurs because sorghum requires less soil moisture than any other crop in the Lake Kariba District. Moreover, the allocation of all land to the production of

Table 5.11 Summarized results for sensitivity analysis for the risk parameter β for the stochastic model in the "without irrigation" framework.

Risk Parameter β (k million)	Target Revenue (k million)	Expected Gross Margin (k million)	Land use allocation to crops in hectares		
			Sorghum	Soyabeans	Rice
0	20	14.1	59,714	15,812	0
4	20	18.2	45,614	43,570	30,070
6	20	18.2	45,614	43,570	30,070
8	20	18.2	45,614	43,570	30,070
10	20	18.8	75,110	51,234	0
12	20	18.8	75,110	51,234	0
14	20	19.4	142,514	0	0
16	20	19.4	142,514	0	0

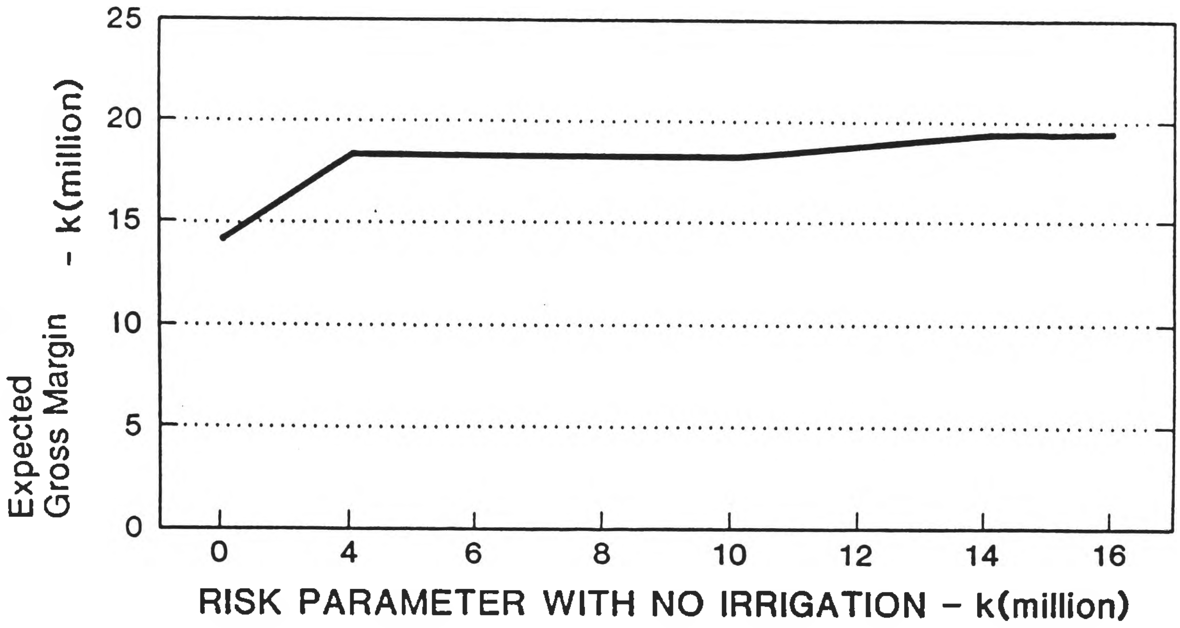


Figure 5.6 Risk parameter β and expected gross margin in the "without irrigation" framework.

sorghum ensures the optimal utilization of limited soil moisture in the area which is caused by the stochastic nature of rainfall since this option depends entirely on rainfall. To sum up, the result of this sensitivity test indicates that if risk taking behaviour is on the increase, then in the context of no irrigation, land should be allocated to the crop that displays the least moisture requirement. In this case it is sorghum.

5.3 Comparison of the application of the frameworks for the "with irrigation", the "without irrigation" options and the existing cropping pattern.

Results from the "with irrigation" and the "without irrigation" options and the existing situation are compared in terms of their cropping pattern, net present values and multiplier effects. Although the "with irrigation" option was tested with deterministic and stochastic frameworks, the comparison herein is confined to the results of the stochastic framework. This follows the earlier rationalization that the stochastic framework represents reality more adequately than the deterministic framework. The comparison of the results of the "with irrigation" and the "without irrigation" frameworks and the existing situation is presented in Table 5.12. A brief discussion of each component of this table is presented below.

5.3.1. Comparison with regards to cropping pattern.

As can be observed from Table 5.12, the comparison of cropping patterns is performed on the basis of having and not having the two policy goals.

There is a great deal of similarity in the types of crops grown between the "with irrigation" option and the existing situation. This is

Table 5.12 **Comparison between "with irrigation", "without irrigation" and existing cropping pattern in the Lake Kariba District under the stochastic framework.**

Activity	With Irrigation				Without Irrigation				Existing Situation as of 1985				
	Maize (ha)	Cotton (ha)	Sorghum (ha)	Gross Margin (k million)	Sorghum (ha)	Rice (ha)	Soyabeans (ha)	Gross Margin (k million)	Maize (ha)	Cotton (ha)	Sorghum (ha)	Sunfl (ha)	Gross Margin (k million)
Cropping Pattern Without Policy Goals													
Wet Season	4,706	157,538	0	85	45614	30,070	43,570	18	3,000	5,000	6,000	1,500	15
Dry Season	4,706	157,538	0	72	---	---	---	---	---	---	---	---	---
Cropping Pattern With Policy Goals (1 & 2)													
Wet Season	4,500	127,744	30,000	65	---	---	---	---	---	---	---	---	---
Dry Season	4,500	127,744	30,000	42	---	---	---	---	---	---	---	---	---
Removal of the credit facility	---	47,000	---	25.27	80,000	---	---	9.2	---	---	---	---	---
NPV for the Kariba Region (a) Without Policy Goals													
Wet Season - k million	---	---	---	745.6	---	---	---	161.4	---	---	---	---	140.4
Dry Season - k million	---	---	---	631.4	---	---	---	---	---	---	---	---	---
(b) With Policy Goals													
Wet Season - k million	---	---	---	614.0	---	---	---	---	---	---	---	---	---
Dry Season - k million	---	---	---	500.0	---	---	---	---	---	---	---	---	---
NPV/household (a) Without Policy Goals													
Wet Season - k million	---	---	---	62,133	---	---	---	13,450	---	---	---	---	11,693
Dry Season - k million	---	---	---	52,616	---	---	---	---	---	---	---	---	---
(b) With Policy Goals													
Wet Season - k million	---	---	---	51,167	---	---	---	Infeasible	---	---	---	---	---
Dry Season - k million	---	---	---	41,667	---	---	---	---	---	---	---	---	---
Regional Spending Multiplier effects (a) Without Policy Goals													
Wet Season - k million	---	---	---	1,245	---	---	---	270	---	---	---	---	234
Dry Season - k million	---	---	---	1,054	---	---	---	---	---	---	---	---	---
(b) Multiplier Effect with Policy Goals													
Wet Season - k million	---	---	---	1,025	---	---	---	---	---	---	---	---	---
Dry Season - k million	---	---	---	835	---	---	---	---	---	---	---	---	---

more true when one considers that maize and cotton are present in both situations. The cropping pattern in the "without irrigation" option is quite different. However, land allocation to the various crops is highest in the "with irrigation" option. This is followed by the "without irrigation" option, and the lowest land allocation to crops is in the existing situation. Moreover, the "with irrigation" option has the greatest advantage over the others because crops can be grown in both seasons, namely the wet and dry seasons. Crops cannot be grown during the dry season in the "without irrigation" and the existing situation, because crop production in these options depends entirely on rainfall, and rainfall is virtually non-existent during the dry season (see chapter 3, section 3.1).

In terms of gross margins, the "with irrigation" option has the highest gross margin in both seasons. Revenue for the "without irrigation" and the existing situation is extremely low and is derived only from the wet season.

With regards to policy goals, these can be satisfied only if the "with irrigation" option is adopted. The other options do not accommodate the policy goals because they depend entirely on rainfall and rainfall is insufficient to meet these policy goals.

5.3.2 Net present value

The net present value (NPV) for the "with irrigation", the "without irrigation" and the existing situation options was calculated using a five percent discount rate over a time horizon of twenty five years. The net income generated by the model was assumed to remain constant, that is, be an annuity.

As expected the net present values of the "with irrigation" option are the highest in both seasons and at both levels, namely the regional and the household levels. The lowest net present values are observed in the existing situation. This holds true at both the regional and household levels.

5.3.3 Multiplier effects

It was assumed that the multiplier effect in this instance would involve an increase in consumption expenditure within the Lake Kariba District. The following formula was used (Begg, Fischer and Dornbusch, 1987; Powell, 1987):

$$k = \frac{1}{1\text{-}b} \text{ x NPV}$$

where:

k = spending multipliers

b = marginal propensity to consume

NPV = net present value

The marginal propensity to consume (b) of 0.7 was used in this study. This was obtained from decision makers in the Lake Kariba District during the 1986 survey. The net present value (NPV) used in this study are those of Table 5.12. The above formula was used in this study because it suits the existing situation in the Lake Kariba District, namely a situation where data is sparse.

Using the above formula, spending multipliers for the Lake Kariba District are calculated and their results are reported in the last row of Table 5.12. As indicated in this table, the spending miltiplier effect is nearly five times more in the "with irrigation" option than in the "without irrigation" option.

5.4 Concluding remarks

From the above discussions of this chapter, one would conclude that the "with irrigation" option is clearly desirable. This conclusion is based on the following factors:

(a) The gross margin derived from the "with irrigation" option is almost five times higher than that derived from the existing situation and the "without irrigation" option. This clear superiority of the "with irrigation" option is also manifested in terms of NPV and the mulitplier effect.

(b) Although the existing situation and the "without irrigation" option show diversified cropping pattern, they fail to fulfill the two policy goals, namely that at least 19,500 hectares of cotton and 30,000 hectares of sorghum be produced. On the other hand, the "with irrigation" option not only shows a diversified cropping pattern but also fulfils the policy goals.

(c) Whilst crop production in the "with irrigation" option can be performed in both seasons, namely the wet and the dry, this is not possible under the existing situation and the "without irrigation" option. This is because the existing situation and the "without irrigation" option depend entirely on rainfall and virtually no rainfall occurs in the dry season.

(d) Whilst risks are minimized under the "with irrigation" option they are prominent in the existing situation and the "without irrigation" option.

This is evident from the observation that in the context of "with irrigation" the size of the expected gross margin and the pattern of resource allocation remain relatively stable, despite variations in the size of the risk parameter (β). However, this is not the case when the irrigation option is absent. That is, in the context of "without irrigation", increases in the size of the risk parameter result in variations in gross margin as well as distinct changes in the pattern of resource allocation to low risk crops; that is, crops that have low soil moisture requirements.

(e) The superiority of the "with irrigation" option in terms of generating a much higher income has been also demonstrated by raising the cost of irrigation. That is, when irrigation was made unrealistically expensive (in the sensitivity tests) by raising the costs by nearly 142 times the estimated cost, the cropping pattern shifts to sorghum which is a low income and a low risk crop. Yet the annual income with irrigation still exceeds that of the "without irrigation" option due to the ability to grow crops in both seasons.

Although the provision of irrigation results in the generation of a much higher income, relative to not having irrigation, the importance of the access to credit should not be overlooked. As illustrated previously in the context of "with irrigation", the removal of the credit facility results in a decline in gross margin amounting to k60 million. That is, the expected gross margin falls to k25.27 million. Further, there is also an under utilisation of resources with only 47,000 hectares of cotton being grown. Despite this drop in gross margin and the underutilisation of resources when the credit facility is withdrawn, the "with irrigation" option generates almost 1.4 times the gross margin generated in the context of "without irrigation".

Despite these advantages which the "with irrigation" option has over other options, this option has been criticized by several scientists (Vermeer, 1981; Banda, 1985; Scudder, 1986; Glantz, 1987 and Barrow, 1987) on the grounds that in most developing countries where irrigation has been adopted, cash crops tend to dominate food crops. This criticism cannot be dismissed offhand given the fact that both food and cash crops are essential for the Lake Kariba District. To answer this criticism one needs to analyse the trade-offs between the objectives of income maximization and food stability. Hence the "with irrigation" framework is adapted for the analysis of trade-offs. This adaptation and subsequent application is considered in Chapter 6.

CHAPTER 6 TRADE-OFFS FOR INCOME MAXIMIZATION AND FOOD STABILITY OBJECTIVES IN THE "WITH IRRIGATION" FRAMEWORK.

The analysis performed so far has been confined to the pursuit of a single social objective, namely income maximization. However, a review of past decisions taken in the area, and discussions carried out with decision makers, indicate that decision makers are concerned not only with income maximization but also with other social objectives. These other objectives include stable food production, environmental quality, employment, reduction of poverty and health. In this list of objectives, food stability appears to be the dominant objective, given that the study area is prone to frequent incidents of drought.

As indicated previously, decision makers have consistently put forward policies to promote the allocation of resources for food crops such as sorghum, even though higher incomes can be earned from cash crops such as cotton. Hence, this chapter deals with the trade-offs that have to be considered between income maximization and food stability objectives.

6.1 Income Maximization and Food Stability Objectives

It is assumed here that the objective of "income maximization" is pursued by way of growing cash crops, and that the objective of "food stability" is pursued by way of growing food crops. The conflicts that prevail between these objectives was indicated in Chapter 5. For example, it was shown (in section 5.1.2) that enforcing sorghum (which is a food crop) into the model solution that contains only cash crops, results in a marked drop of income. This drop in income was k9 million for the wet season and k12 million for the dry season.

The analysis of trade-offs between these objectives gives decision makers a range of options from which they can decide how much of each type of crop to produce. Further, the trade-off analysis would also enable the identification of efficient solutions which minimize the conflicts between objectives. The identification of such efficient solutions could not be done in Chapter 5 because the models therein were specified within the framework of a single objective, namely the maximization of income (gross margins). Since the results of Chapter 5 nominate the "with irrigation" option the analysis of trade-offs is also confined to this option. Hence, the Target MOTAD model for the "with irrigation" option is now adapted to include, in addition to income maximization, the objective of food stability.

Barbier (1989) points out that the distinction between food and cash crops is not clear cut. He says that a cash crop may be sold at home or abroad and may be either a food or a non-food commodity. He classifies cotton, sunflower and soyabeans among cash crops. On the other hand, he describes food crops as having a dual character in that whilst some of it may be retained for domestic consumption, the surplus may be sold for cash. Hence, it is precisely this dual character of food crops which makes a clear cut distinction between food and cash crops very difficult. However, despite this difficulty, Barbier regards all cereal and tuber crops as food crops. Hence, following Barbier (1989) the food crops in this study are: maize, sorghum, rice and wheat; and the cash crops are: cotton, sunflower and soyabeans. All these crops have been used in the deterministic and Target MOTAD models in Chapters 4 and 5. It will be assumed herein that the production of food crops contribute to the food stability objective, whilst the production of cash crops will contribute to the income maximization objective.

6.2 The methods for trade-offs analysis

A trade-off as defined by Cohon (1978) represents the amount by which one objective must be sacrificed in order to obtain an increase in the other objective. Three methods are normally used to generate trade-offs. These are the weighting, the constraint and the multicriterion methods. Detailed reviews of these methods are provided in Cohon (1978); Willis and Perlack (1980); Goicoechea, Hansen and Duckstein (1982); and Romero, Amador and Barco (1987). Of these methods, the multicriterion method is the least used, and is hence not considered herein. The weighting and constraint methods are briefly explained below and the Target MOTAD model used in this study can be easily adapted for the application of these methods.

6.2.1 The weighting method

The weighting method gives a weight to each objective and then sums the objectives together so as to obtain what Cohon (1978) calls noninferior or efficient solutions. Thampapillai and Sinden (1979) point out that the weighting method is based on a defined range of weights for each objective such that the maximization of each objective in the objective function is done on the basis of weights assigned to each of them. The parameterizing of weights, which may lie between zero and one (Thampapillai, 1976; and Thampapillai and Sinden, 1979) or which can take any number, that is, from zero to infinity (Sankhayan, Prihar and Cheema, 1988) creates an efficient set of solutions which constitutes the trade-off function.

Following Thampapillai and Sinden (1979), Cohon (1978) and Goicoechea, Hansen and Duckstein (1982), the mathematical specification of the weighting method is as follows:

Maximize $Z = (1 - \alpha)\,[Z_1(X)] + (\alpha)\,[Z_2(X)]$

Subject to:

$A(X) \leq B$; and

$$X \geq 0, \qquad (6.1)$$

where:

$Z_1(X)$ represents income maximization objective

$Z_2(X)$ represents the food stability objective

X represents the vector of decision variables

A(X) represents the usual matrix of resource requirements;

B represents the vector of resource availabilities; and

α represents the weight attributed to the food stability objective.

The weight α ranges between 0 and 1. Hence, the weight on the income objective, namely $(1 - \alpha)$ is implied by the value of α.

The trade-off function is generated by solving the model for various values of α. For example, when $\alpha = 1$ the only objective to be maximized is food stability; and when $\alpha = 0$, the only objective to be maximized is income. So, when $\alpha = 1$, all resources are allocated to the food stability objective; and when $\alpha = 0$, all resources are allocated to the income objective. If $0 \leq \alpha \leq 1$, the food stability and the income objectives are maximized together in some weighted combinations and the resources are allocated between both objectives. Hence, each point on the trade-off function corresponds to a unique set of values for α

and (1 - α). This relationship between the weights and the two objectives is illustrated in the hypothesized trade-off function in Figure 6.1a.

6.2.2 Constraint Method

The constraint method optimizes one objective while specifying the other objectives as constraints (Haimes, Lasdon and Wismer, 1971; Olagundoye, 1971; Cohon and marks, 1973; Haimes, 1975; and Thampapillai, 1985). The trade-off function is generated by parameterizing the right hand side of the objective that is defined as constraints. The general model specification of the constraint method is as follows:

Maximize $Z_1 (X)$

Subject to: $A (X) \leq B$,

$Z_2 (X) \geq P$; and

$$X \geq 0 \tag{6.2}$$

Where:

$Z_1 (X)$, $Z_2 (X)$ represent the income and food stability objectives respectively;

P represents a prespecified target for the food stability objective; and

A (X) and B are resource requirements and resource availabilities respectively.

The trade-off function can be generated by initially setting the value of P at zero, and then successively raising it to some maximum value. When P is zero all resources are allocated to the income objective. On the other hand, all resources will be allocated to the food

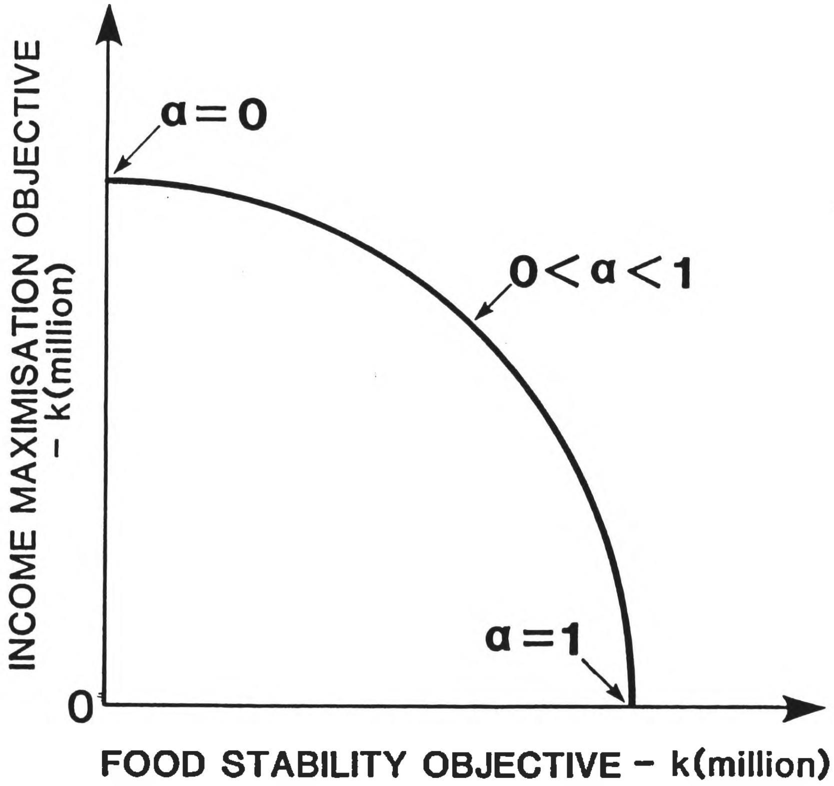


Figure 6.1a Hypothetical figure for the weighting method

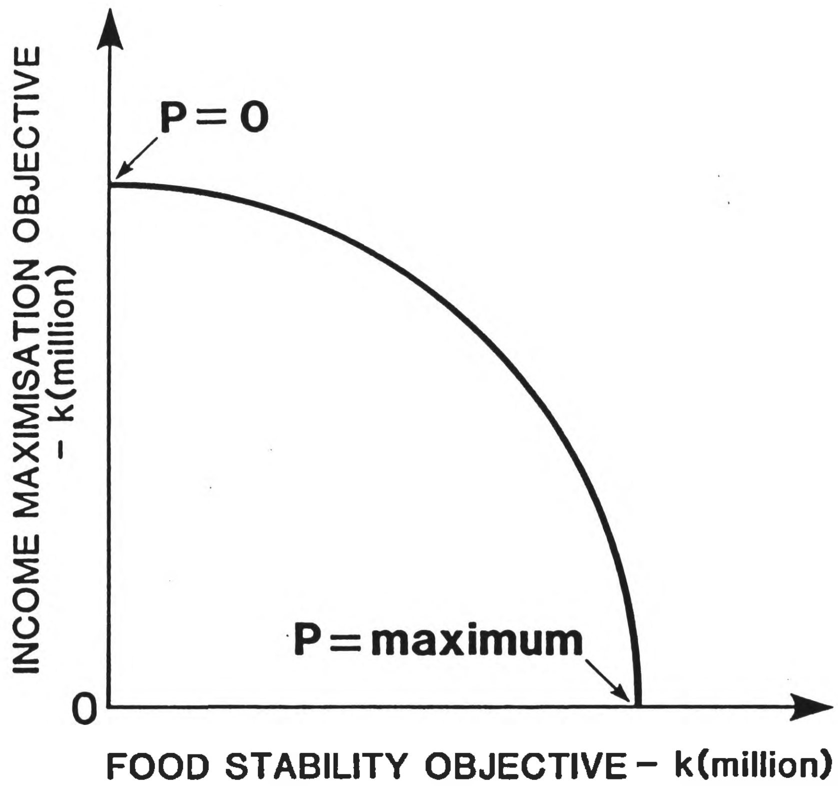


Figure 6.1b
Hypothetical figure for the constraint method

stability objective when P is sufficiently large. A hypothetical trade-off function from this method is shown in Figure 6.1 (b) above.

Although both the weighting and constraint methods can be applied with the Target MOTAD model, herein, the weighting method is used. The choice of the weighting method is governed by the inference that each point on the trade-off function that is generated by the weighting method corresponds explicitly to specific values of the weights on the two objectives. Hence, should the values of these weights be known, then the management policy would be a unique point on the trade-off function. Even if the precise values of these weights are not known, and the knowledge of the weights is confined to a range of values, decision makers can be offered the option of making choices from a segment of the trade-off function.

6.3 Application of the Target MOTAD model for Trade-Off Analysis

The Target MOTAD model has to be first adapted for trade-off analysis. This adaptation merely involves the replacement of the objective function presented in Chapter 4, with a weighted objective function. This weighted objective function is:

$$\text{Maximize } Z = 1 - \alpha \left\{ \sum_{q=1}^{5} \sum_{j=1}^{3} \alpha \left(E\,(C_{qij})\,(X_{qij}) \right) - \sum_{q=1}^{5} \sum_{j=1}^{3} K_{qij} W_{qij} - \right.$$

$$\left. \sum_{q=1}^{5} \sum_{j=1}^{3} Ib_{qij} \right\} + \alpha \left\{ \sum_{q=1}^{5} \sum_{j=4}^{7} [E\,(C_{qij})\,(X_{qij})] - \right.$$

$$\left. \sum_{q=1}^{5} \sum_{j=4}^{7} K_{qij} W_{qij} - \sum_{q=1}^{5} \sum_{j=4}^{7} Ib_{qij} \right\} \qquad (6.3)$$

In (6.3) the definition of coefficients (C, K and I) and variables (X, W and b) is the same as that offered in Chapters 4 and 5. However, note that (j = 1, 2 3) represents the cash crops (cotton, sunflower and soyabeans) and (j = 4, 5, 6 and 7) represent the food crops (maize, sorghum, rice and wheat). The objective function in (6.3) in which its expected gross margins are estimated at constant kwacha values is optimized subject to the same constraints as presented in section 4.2 of Chapter 4.

Further, recall that in Chapter 5, two policy goals were introduced. The first goal was that at least 19,500 hectares of cotton must be grown; and the second goal was that at least 30,000 hectares of sorghum must be grown. Accordingly, the trade-off function is derived in the context of four scenarios namely:

(i) without any policy goal;

(ii) with policy goal 1 only;

(iii) with policy goal 2 only; and

(iv) with both policy goals.

6.4 Results of the Application

The aggregated values of each objective generated for each value of α at constant kwacha benefit estimates are presented in Table 6.1 and the resulting trade-off functions for the various scenarios are presented in Figures 6.2a, 6.2b, 6.2c, 6.2d and 6.2e.

From Figure 6.2a, it can be seen that all trade-off functions that were derived in the context of either one or both policy goals are within the trade-off function that was derived in the context of no policy goals. That is trade-off functions ABHK, LGM and LGIJ have all been derived in the context of policy goals, and are within the trade-off function ABC which was derived without any policy goals.

Table 6.1 Trade-Off Values and Cropping Patterns for the Income and Food Stability Objectives without Policy Goals and with Policy Goals 1, 2 and 1 + 2

Weight of Objective	Policy Goals	Income Objective (I) Kwacha (million)	Food Stability Objective (FS) Kwacha (million)	Cropping Pattern Maize (ha)	Cotton (ha)	Sunflower (ha)	Sorghum (ha)
0.00	None	87.73	0	0	158,758	3,486	0
	1	87.73	0	0	158,758	3,486	0
	2	71.47	9.72	0	128,758	3,486	30,000
	1+2	71.47	9.72	0	128,758	3,486	30,000
0.10	None	87.73	0	0	158,758	3,486	0
	1	87.73	0	0	158,758	4,486	0
	2	71.47	9.72	0	128,758	3,486	30,000
	1+2	71.47	9.72	0	128,758	3,486	30,000
0.20	None	87.73	0	0	158,758	3,486	0
	1	87.73	0	0	158,758	3,486	0
	2	71.47	9.72	0	128,758	3,486	30,000
	1+2	71.47	9.72	0	128,758	3,486	30,000
0.30	None	87.73	0	0	158,758	3,486	0
	1	87.73	0	0	158,758	3,486	0
	2	71.47	9.72	0	128,758	3,486	0
	1+2	71.47	9.72	0	128,758	3,486	0
0.40	None	85.39	2.53	4,706	157,538	0	0
	1	85.39	2.53	4,706	157,538	0	0
	2	69.13	12.25	4.706	157,538	0	0
	1+2	69.13	12.25	4.706	127,538	0	30,000
0.50	None	67.86	19.93	37,046	125,198	0	0
	1	67.86	19.93	37,046	125,198	0	0
	2	67.86	13.51	7,046	125,198	0	30,000
	1+2	67.86	13.51	7,046	125,198	0	30,000
0.52	None	67.86	19.93	37,046	125,198	0	0
	1	67.86	19.93	37,046	125,198	0	0
	2	67.86	19.93	37,046	125,198	0	30,000
	1+2	67.86	13.51	7,046	125,198	0	30,000
0.53	None	0	87.29	162,244	0	0	0
	1	10.57	76.80	142,744	19,500	0	0
	2	0	80.87	132,244	0	0	30,000
	1+2	10.57	70.38	112,744	19,500	0	30,000
0.60	None	0	87.29	162,244	0	0	0
	1	10.57	76.80	142,744	19,500	0	0
	2	0	80.87	132,244	0	0	30,000
	1+2	10.57	70.38	113,744	19,500	0	30,000
0.70	None	0	87.29	162,244	0	0	0
	1	10.57	76.80	142,744	19,500	0	0
	2	0	80.87	132,244	0	0	30,000
	1+2	10.57	70.38	112,744	19,500	0	30,000
0.80	None	0	87.29	162,244	0	0	0
	1	10.57	76.80	142,744	19,5000	0	0
	2	0	80.87	132,244	0	0	30,000
	1+2	10.57	70.38	112,744	19,500	0	30,000
0.90	None	0	87.29	162,244	0	0	0
	1	10.57	76.80	142,744	19,500	0	0
	2	0	80.87	132,244	0	0	30,000
	1+2	10.57	70.38	112,744	19,500	0	30,000
1.00	None	0	87.29	162,244	0	0	0
	1	10.57	76.80	142,744	19,500	0	0
	2	0	80.87	132,244	0	0	30,000
	1+2	10.57	70.38	112,744	19,500	0	30,000

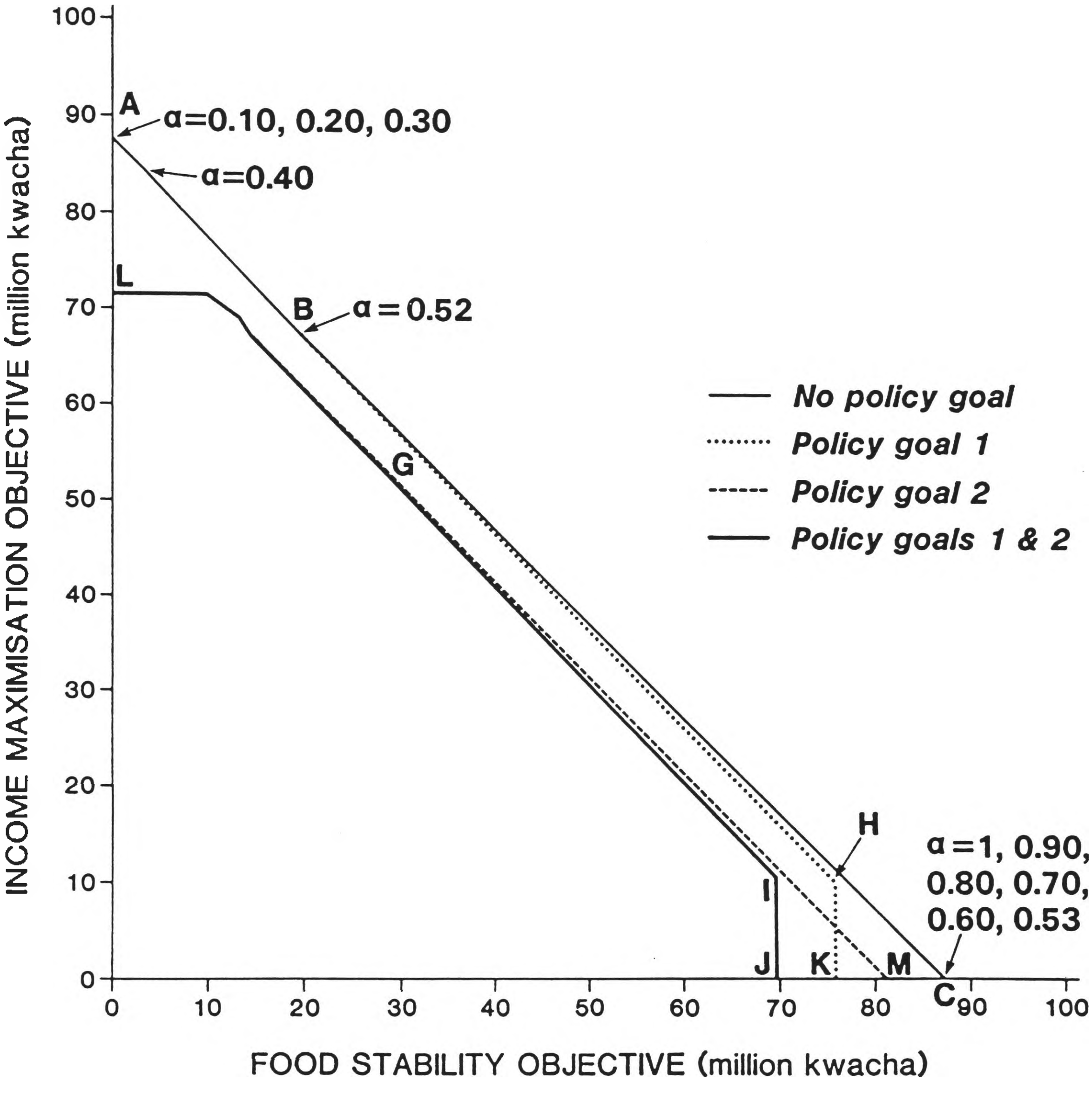


Figure 6.2a Trade-off functions

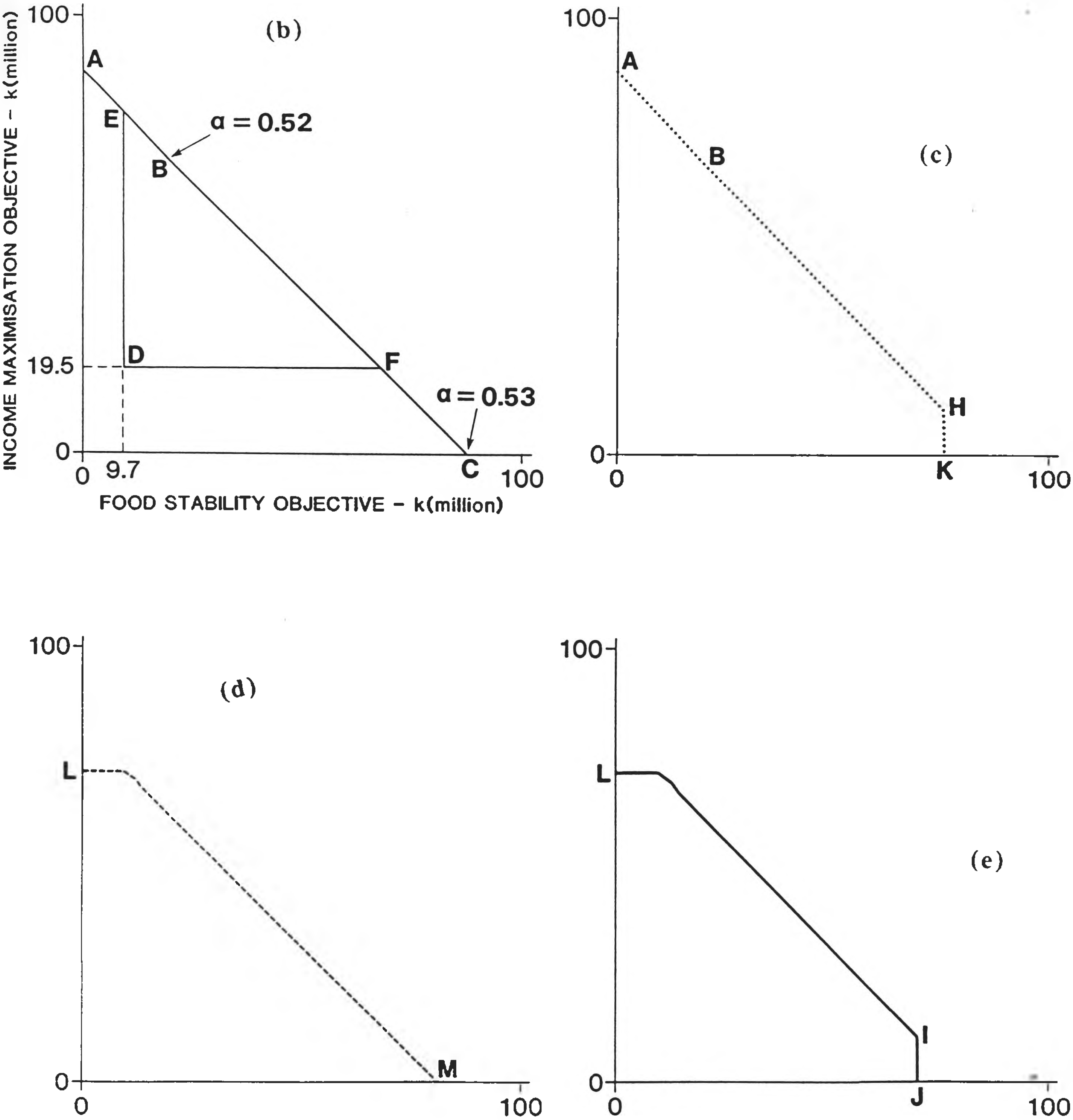


Figure 6.2 Trade-off Functions for Income maximization and Food Stability Objectives with No Policy Goal, Goals 1, 2 and 1 + 2 respectively.

Therefore, the trade-off function, derived in the context of not having any policy goals is a superior set compared to all trade-off functions that are derived in the context of one or more policy goals.

The superiority of the trade-off function ABC rests on the complete utilization of resources at all points of the function. All other trade-off functions depict under-utilization of resources. The most significant under-utilization applies to labour. The under-utilization of labour that is caused by the introduction of policy goals is illustrated in Table 6.2. From this table it is also evident that enforcing the policy goal with respect to sorghum causes more unemployment of labour relative to the enforcement of the policy goal concerning cotton. Therefore it appears that decision makers' stipulation to grow sorghum in the area could create a welfare loss given that unemployment of labour is always regarded as something undesirable. Given that the trade-off function of without any policy goals represents an economically efficient set, that is one which does not permit unemployment of resources all policy decisions must be made with reference to trade-off function ABC. Hence, it may be prudent to adopt the pattern of resource allocation dictated by the solution on trade-off function ABC and import the sorghum requirement should such requirement be regarded essential. From Table 6.1 it can be seen that the trade-off function without any policy goals excludes the production of only cotton and/or maize and/or sunflower.

With respect to the trade-off function for ABC several observations can be made. These are discussed below.

All resources are allocated for the income maximization objective for $\alpha \leq 0.30$; and all resources are allocated to the food stability objective for $\alpha \geq 0.53$.

Table 6.2 Utilization of labour under different scenarios

	Without any policy goal	With policy goal 1 only	With policy goal 2 only	With both policy goals
1. Labour utilization when $\alpha = 0 \leq \alpha \leq 0.52$	5,926,673	5,926,673	5,759,033	5,759,033
2. Under utilization of labour relative to the scenario of no policy goal ($0 \leq \alpha \leq 0.52$)		0	167,640	167,640
3. Labour utilization when $0.53 \leq \alpha \leq 1.00$	5,926,673	5,279,753	5,107,673	4,829,673
4. Under utilization of labour relative to the scenario of no policy goal ($0.53 \leq \alpha \leq 1$)		646,920	819,000	1,097,000

For values of α, namely $(0 < \alpha \leq 0.52)$, the income maximization objective dominates the food stability objective. However, a small increase in α, that is from $\alpha = 0.52$ to $\alpha = 0.53$ creates a significant shift in the pattern of resource allocation. Hence, the conflict between objectives is greatest between $\alpha = 0.52$ and $\alpha = 0.53$. This conflict can be defined as the reduction in the value of an objective when the weight on the other objective is raised. The basis for the measurement of conflict can be explained following Thampapillai and Sinden (1979) as follows:

Let the value of the income maximization when $\alpha = 0$, be VP_1. Let the value of the income maximization objective for values of $0 < \alpha \leq 1$, be VP_2; the difference, $(VP_1 - VP_2)$ is, indicator of the magnitude of the conflict. In fact, $(VP_1 - VP_2)$ is a measure of the opportunity cost of the food stability objective. The information on conflict is presented in Table 6.3. From this table it is evident that the conflict increases by k67.86 million when α is raised from $\alpha = 0.52$ to $\alpha = 0.53$.

Hence, from the point of view of decision making, the value of α appears to be crucial; and the exact value of α is not known. However, the knowledge that the decision makers have stipulated two policy goals can be used to narrow the search for a point on the trade-off function ABC. The policy goals that at least 19,500 hectares of cotton must be grown corresponds to an expected gross margin of k19.5 million; and the policy goal that at least 30,000 hectares of sorghum must be grown corresponds to an expected gross margin of k9.7 million. Hence, the minimum attainment of the target of these two goals corresponds to point D in Figure 6.2 b. Note that the movement from D to any point on segment EF represents a Pareto improvement. Hence, the decision makers can be advised to choose a resource

Table 6.3 Measurement of Conflict Between Income and Food Stability Objectives

Weight	$(VP_1 - VP_2)$ = opportunity cost of the food stability		
α	Kwacha Million		Kwacha Million
$0 < \alpha \leq 0.30$	(87.73 - 87.73)	=	0
$\alpha = 0.4$	(87.73 - 85.39)	=	2.34
$0.5 \leq \alpha \leq 0.52$	(87.73 - 67.86)	=	19.87
$0.53 \leq \alpha \leq 1.00$	(87.73 - 0)	=	87.73

allocation policy on segment EF. Note that all points on this segment have values of α less than 0.53 and greater than 0.40. Any further choice of resource allocation policy within this segment EF, is possible only if the value α is known. Should the income maximization objective be dominant then it is plausible that the search for policies can be further narrowed to segment EB. This is because, as indicated previously, conflict between the two objectives (in terms of the opportunity cost of the food stability objective) is minimal up to point B; that is, $0 < \alpha \leq 0.52$.

6.5 Some concluding remarks

In Chapter 5, the "with irrigation" strategy was nominated as the desirable strategy. When the first policy goal was introduced, the "with irrigation" strategy was defined as the cultivation of 125,198 hectares of cotton and 37,046 hectares of maize. Similarly, when the second policy goal was introduced the "with irrigation" strategy was defined as the cultivation of 132,244 hectares of cotton, and 30,000 hectares of sorghum.

However, the trade-off analysis in this chapter indicates that enforcing the cultivation of sorghum can result in unemployment of labour. Enforcing the cultivation of cotton also results in a slight unemployment of labour for values of $\alpha > 0.52$. This is shown in Figure 6.2a, where the trade-off function with policy goals is identical to the superior trade-off function until $\alpha = 0.52$. Hence, it is pertinent to conclude that sorghum should be excluded from production should unemployment of labour be deemed undesirable.

CHAPTER 7 CONCLUSIONS

A summary of this thesis is presented in the first section of this chapter. This is followed by a discussion of some implications of the results. In the second section, some possibilities for further extensions of the research demonstrated in this thesis are considered.

7.1 Summary of the thesis

To recapitulate, the objectives of this thesis were to:

(i) formulate decision frameworks for the "with irrigation" and "without irrigation" strategies,

(ii) empirically demonstrate the applicability of these decision frameworks to the Lake Kariba District;

(iii) illustrate management strategies that are pertinent to the district; and

(iv) analyze trade-offs between income maximization and food stability objectives.

Two types of frameworks were developed; one for the "with irrigation" option and the other for the "without irrigation" option. The frameworks for the "with irrigation" option included deterministic as well as stochastic frameworks, while the framework for the "without irrigation" option was solely stochastic. The frameworks for the "with irrigation" option consisted of: a rainfall simulator, a mathematical programming model and a monitor of lake water levels. The mathematical programming model was a deterministic linear programming model in the deterministic framework, whilst in the stochastic framework it was a Target MOTAD model. The components of the framework of the "without irrigation" option were: a rainfall simulator and a Target MOTAD model.

The relative desirability of the "with irrigation" and the "without irrigation" options was determined by comparing the incomes generated under both options. Since it was observed that the results of the deterministic framework were less relevant, the comparison was confined to the results of the application of the stochastic frameworks that were developed for each option. In terms of maximizing income the "with irrigation" option was found to be far superior to the "without irrigation" option. The difference in income between the two options was k67 million. Both the "with irrigation" and the "without irrigation" options exceed the present patterns of resource allocation in the district.

The results of the application of the framework for the "with irrigation" option recommend the allocation of resources to cotton and maize. The application of the framework for the "without irrigation" recommends the allocation of resources to sorghum, soyabeans and rice.

The incorporation of policy goals of minimum hectarage for sorghum and cotton resulted in a lowering of income for the "with irrigation" option, whilst the framework became infeasible for the "without irrigation" option.

The community of the study area pursues not only the objective of income maximization but also other objectives. Of the other objectives, food stability is perceived as a dominantly important objective. Hence, the stochastic framework for the "with irrigation" option was adapted to demonstrate the trade-offs that are possible between the objectives of income maximization and food stability objectives. The application of this adapted framework resulted in the demonstration of a trade-off function for the "with irrigation" option. This trade-off function is an efficient frontier, in that it involves full utilization of resources. At one extreme of the frontier, all resources are allocated to the income generating enterprises, namely cotton and sunflower. At the other extreme the resources are allocated to maize which is a food crop. Each point on the trade-off function corresponds to a set of weights (which ranges between 0 and 1) for the food stability objective. The conflict between objectives appears to be highest when this weight is between 0.52 and 0.53. The incorporation of the policy goals results in an under utilization of resources especially labour.

7.2 Implications of the results

This thesis has shown that all the frameworks that were developed in this study are applicable. Had the deterministic and stochastic frameworks of the "with irrigation" option generated similar results, the need for applying the stochastic framework would have been weakened. However, as illustrated in Chapter 5, the results were different and the stochastic framework was preferred in that it resembles reality more closely than the deterministic framework. Even if the decision makers are unable to implement the irrigation option (due to external constraints such as limited investment capital) the usefulness of this study is not diluted. This is because the application of the framework for the "without irrigation" option has demonstrated patterns of resource allocation that generate higher income than the existing patterns of resource allocation.

Regardless of whether the "with irrigation" option or the "without irrigation" option is adopted, the results of this study indicate that there has to be a change in the present patterns of resource allocation. In the context of only the income objective and "with irrigation", this change will involve a shift from sorghum, cotton, maize and sunflower of the present farming practices to only cotton and maize in the "with irrigation" option. In the context of the income objective and the "without irrigation" option, this change will involve the replacement of cotton, maize and sunflower with rice and soyabeans.

The trade-off analysis was confined to the "with irrigation' option since it was the preferred option. The pattern of resource allocation in the trade-off framework would depend on the weight that is attached to the food stability objective. If this weight is less than 0.50, (that is the income objective is dominant), the pattern of resource allocation ranges between growing only cotton to growing mostly cotton and some maize. On the other hand, should the food stability objective be dominant, that is the value of weight is larger than 0.50, then the pattern of resource allocation ranges between growing some cotton and mostly maize to growing only maize.

If the "with irrigation" option is adopted, the results demonstrate a significant increase in the volume of output relative to present output. This is so regardless of whether the output consists of cash crops or food crops or a mixture of both. Therefore, an important implication of the result shown in this study is that the adoption of the "with irrigation" option would have to be accompanied by the development of storage and marketing facilities. Further, the importance of access to credit facilities should also be noted. As indicated in Chapter 5, the removal of the credit facility results in a marked drop of income in the context of both "with" and "without" irrigation options.

7.3 Directions for future research in the study area

Future research in the area could take two dimensions. These are:

(i) strengthening data base; and

(ii) developing other programming models for the drought situation.

Each of these is briefly considered below.

Strengthening data base

Data scarcity was identified in Chapter 2 as the major reason for restricting this study's definition of drought to evapotranspiration. The ideal situation was to define drought in terms of reduction in crop yields due to soil moisture stress at various stages of plant growth (Shaw, 1970 and O'Brien, 1981). Such a definition of drought entails the availability of experimental data on soil moisture stress and crop yields collected on a daily basis. This type of data is required for making decisions concerning time to irrigate, cost of irrigation and revenue to be obtained at various stages of plant growth.

Lack of data has also been cited in Chapter 2 as the major reason for not using in this study other pertinent models of decision making. These include the models of: discrete stochastic programming, dynamic programming, chance constrained programming and quadratic programming.

Developing other types of programming models

A major weakness of the Target MOTAD model lies in its assumption that decision makers make decisions on a long term period, say a six year plan period and that changes in decisions occur only after say, the six year plan period. This assumption may be restrictive, especially for decisions involving agricultural production. According to Rae (1971a, 1971b); Anderson, Dillon and Hardaker (1977) and O'Brien (1981) farmers plan production activities on an annual basis and adapt their farming practices on the basis of changing events during the year. They suggest discrete a stochastic programming model as a suitable programming technique to use in situations where decisions are made on an annual basis and are adaptable as events change. The two programming models, namely the Target MOTAD and the discrete stochastic programming model would complement each other if they can be integrated. The possible method of integration could involve the development of a two-stage sequential framework. In the first stage a discrete stochastic programming model can be used to generate a set of annual decisions over a planning period. These decisions can in turn can become inputs of a Target MOTAD model in the second stage.

The "with irrigation" and the "without irrigation" frameworks were developed in this study as separate and distinct frameworks. This approach is justified on the premise that the "with irrigation" and the "without irrigation" options are two mutually exclusive options.

However, another option that may be assessed would be one where irrigation is used as a supplementary measure in an agricultural practice that relies on rainfall. The framework to assess such an option could be a time sequenced one consisting of a dynamic programming model and a Target MOTAD model. The dynamic programming model could determine when to irrigate and when not to irrigate if:

(i) each year of the planning period is regarded as a stage;

(ii) predicted rainfall values over the planning period are nominated as state variables; and

(iii) "to irrigate" and "not to irrigate" are decision variables.

The Target MOTAD model could then be used as a second stage model to determine the pattern of land use for each year of the planning period for the relevant decision that was nominated by the dynamic programming model. A similar strategy may also be derived by formulating a recursive linear programming model of land use.

Whilst in this study the Target MOTAD model has been adapted in Chapter 6 to derive trade-off functions for two objectives, namely the income maximization objective and the food stability objective, future research should attempt to use the Target MOTAD model to derive trade-offs for more than two objectives. For example, the introduction of policy goals in the modified Target MOTAD model of Chapter 6 results in under-employment of labour in the Lake Kariba District (see Table 6.3). Moreover, given the fact that environmental issues dominate implementation of projects, especially those involving irrigation (Kennedy, 1986) the inclusion of other objectives in analyzing trade-offs is essential. Thus, an extension to this study would involve the inclusion of other relevant non-commensurable objectives such as income distribution, soil conservation measures, employment and quality of life. Since, these non-commensurable objectives cannot be quantified in monetary values and other established yardsticks (Thampapillai, 1976), the incorporation of any non-commensurable objective will also require the development of methods to quantify such objectives.

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APPENDIX I

MAP SHOWING TRANSMISSION LINES FROM KARIBA DAM TO ZAMBIA AND ZIMBABWE

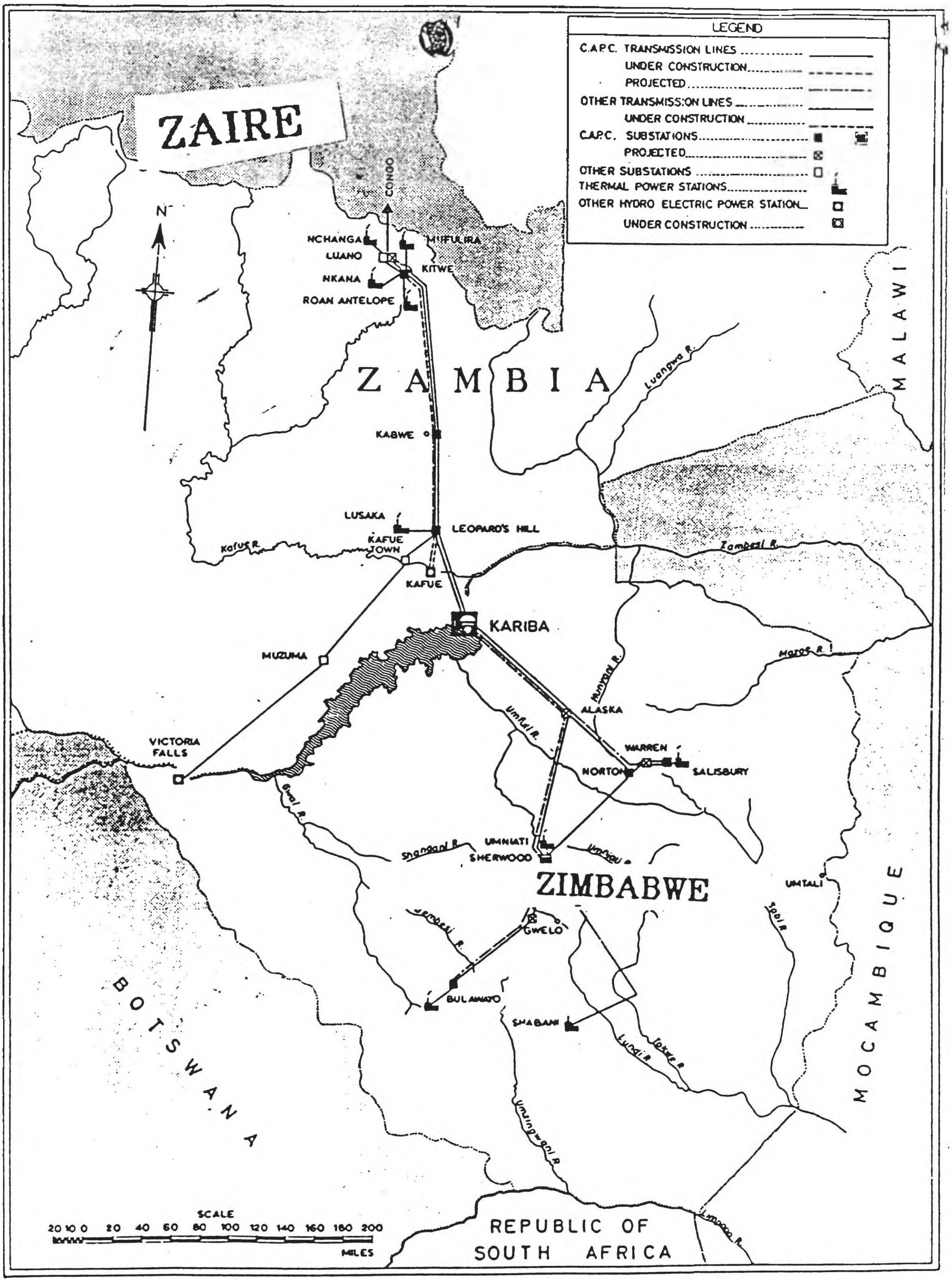


Figure 1A Transmission lines for Kariba Dam

APPENDIX II

MONTHLY RAINFALL PATTERNS IN THE LAKE KARIBA DISTRICT 1952/53 - 1985/86

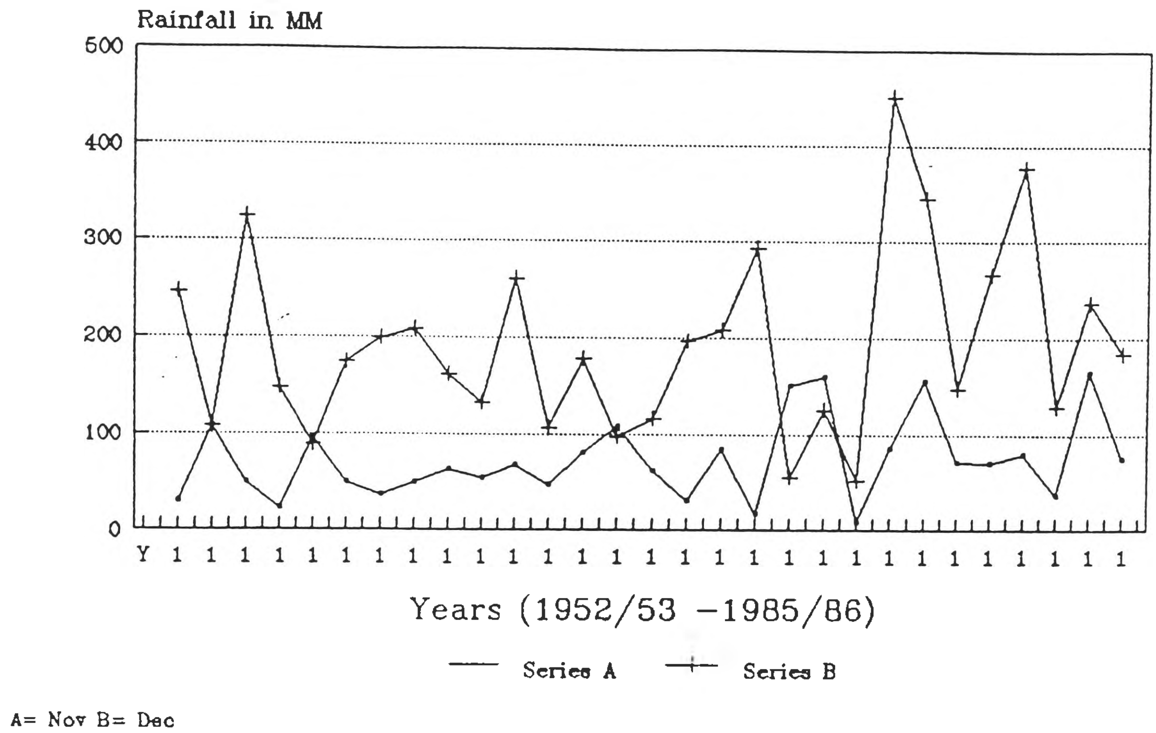
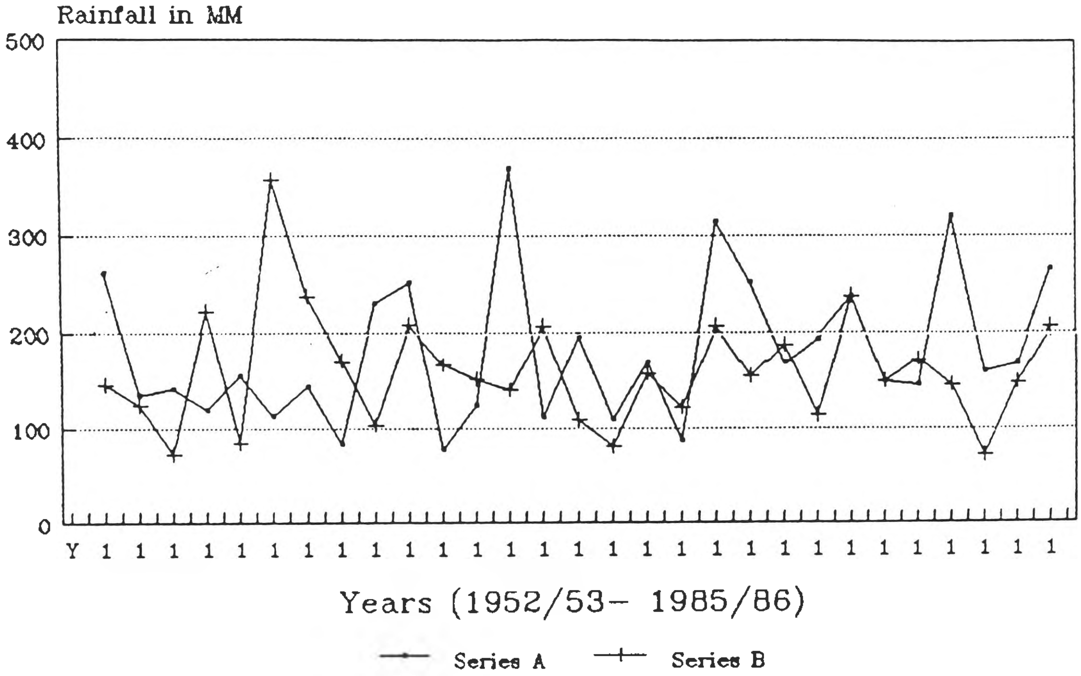
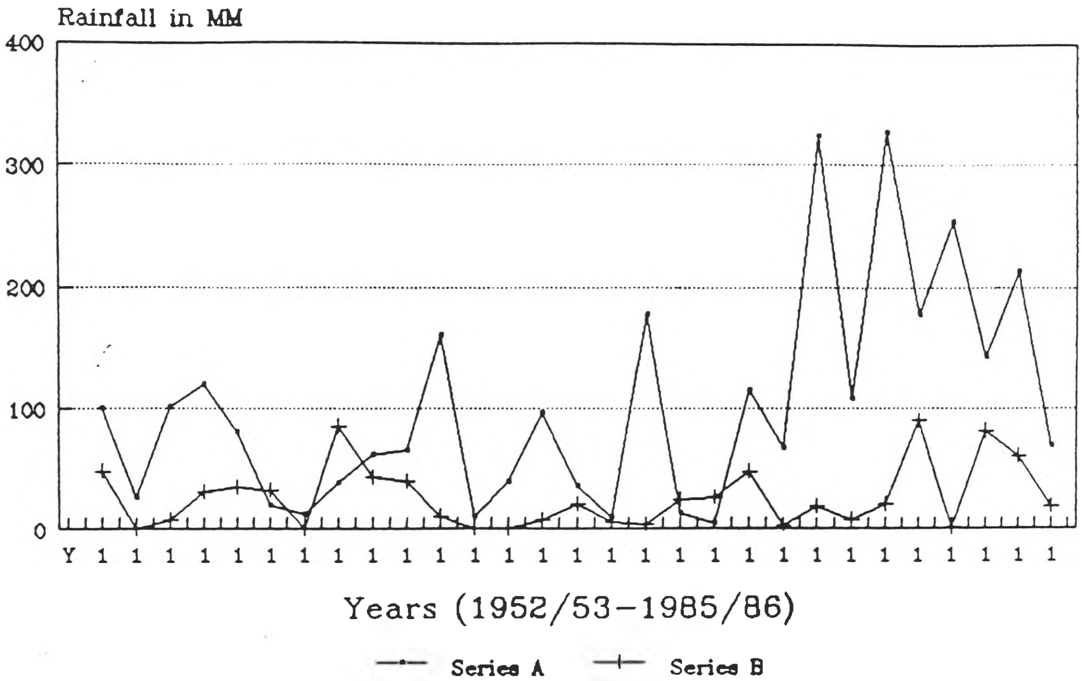


Figure 2A Rainfall pattern for November and December 1952/53 to 1985/86



A= Jan B=Feb

Figure 3A Rainfall pattern for January and February 1952/53 to 1985/86



A = Ma B = Apr

Figure 4A Rainfall pattern for March and April 1952/53 to 1985/86

APPENDIX III

ACTUAL AND SIMULATED RAINFALL DATA FOR THE LAKE KARIBA DISTRICT

Table 1A **Actual annual rainfall data in the Lake Kariba District for the wet and dry seasons 1952/53 to 1985/86**

Year	Wet Season Rainfall (millimetres)	Dry Season Rainfall (millimetres)	Total Annual Rainfall (millimetres)
1952/53	830.2	0	830.2
1953/54	500.2	15.5	515.7
1954/55	700.3	15.7	716.0
1955/56	662.0	39.1	701.1
1956/57	540.4	31.2	571.6
1957/58	743.8	16.2	760.0
1958/59	628.8	31.5	660.3
1959/60	635.4	24.9	660.3
1960/61	662.7	1.0	663.7
1961/62	750.4	23.5	773.9
1962/63	744.3	2.0	746.3
1963/64	439.4	8.1	447.5
1964/65	806.0	12.4	818.4
1965/66	626.4	19.3	645.7
1966/67	541.7	5.8	547.5
1967/68	432.9	27.9	460.8
1968/69	802.1	0	802.1
1969/70	555.2	21.1	576.3
1970/71	757.6	0.3	757.9
1971/72	855.3	1.8	857.1
1972/73	490.9	0	490.9
1973/74	1188.3	47.7	1236.0
1974/75	1090.8	23.6	1114.4
1975/76	865.7	32.4	898.1
1976/77	925.4	23.0	948.4
1977/78	1178.1	31.8	1209.9
1978/79	621.0	7.2	628.2
1979/80	992.2	27.8	1020.0
1980/81	817.1	52.4	869.5
1981/82	673.2	21.0	694.2
1982/83	402.9	114.2	517.1
1983/84	463.3	18.3	481.6
1984/85	727.5	11.7	739.2
1985/86	876.5	11.4	887.9

Source: **Department of Meteorology, Zimbabwe, several issues**

Table 2A Simulated annual rainfall data in the Lake Kariba District for the wet season

Wet Season Rainfall (millimetres)	Wet Season Rainfall (millimetres)	Wet Season Rainfall (millimetres)
742.5	662.0	576.4
544.3	802.1	760.0
437.4	490.9	628.2
1117.8	931.7	745.3
923.1	439.4	1216.2
729.0	540.2	868.5
631.5	635.3	660.3
621.0	750.4	739.2
490.9	402.9	1209.9
765.3	727.5	517.1
437.4	817.1	773.7
631.8	744.3	662.0
826.2	432.9	802.1
1020.6	555.2	517.1
437.4	576.4	964.1
1117.8	760.0	1209.9
643.5	460.8	460.8
729.0		
635.4		
Wet Season Rainfall (millimetres)	**Wet Season Rainfall (millimetres)**	**Wet Season Rainfall (millimetres)**
555.2	571.6	628.2
743.8	447.6	460.8
432.9	964.1	760.0
621.0	490.9	576.4
744.3	803.4	402.9
1188.4	948.1	750.4
817.1	701.1	635.4
628.8	571.6	540.4
727.5	660.3	439.4
1178.1	773.9	931.7
402.9	517.1	490.9
750.4	12098.9	802.1
635.4	739.2	925.4
439.1	660.3	662.0
931.7	869.5	635.4
802.1	1216.2	1188.3
925.4	745.3	
662.0		

Table 2A Simulated annual rainfall data in the Lake Kariba District for the wet season (cont.)

Wet Season Rainfall (millimetres)	Wet Season Rainfall (millimetres)	Wet Season Rainfall (millimetres)
760.0	439.4	607.5
628.2	931.7	525.9
1216.2	490.9	411.8
660.3	925.4	887.0
1209.9	662.0	803.4
773.9	1188.3	490.9
571.6	744.3	517.1
964.1	432.9	773.9
803.4	555.2	628.2
701.1	743.8	745.3
576.4	1209.9	571.6
555.2	517.1	447.6
743.8	773.9	948.1
432.9	660.3	872.3
621.0	964.1	113.1
744.3	803.4	423.9
1188.3	701.1	699.2
635.4		869.5
490.9		
931.7		
635.4		
628.8		
621.0		
432.9		
743.8		
555.2		
1178.1		
817.1		
744.3		
540.4		
439.4		

Source: Generated by Mini-Tab Software package (1985)

Table 3A **Simulated annual rainfall data in the Lake Kariba District for the dry season**

Dry Season Rainfall (millimetres)	Dry Season Rainfall (millimetres)	Dry Season Rainfall (millimetres)
21.1	22.7	9.7
16.2	39.1	5.0
29.9	31.8	10.7
7.2	0	21.3
1.0	23.5	0.3
27.9	31.2	1.9
52.4	32.4	25.0
31.5	1.3	44.7
11.7	16.2	22.9
31.8	7.2	2.8
114.2	1.0	9.9
23.5	39.1	8.1
24.9	21.1	0
31.2	12.4	0
8.1	0.7	20.3
32.4	29.0	0.5
0		1.0
1.3		
Dry Season Rainfall (millimetres)	**Dry Season Rainfall (millimetres)**	**Dry Season Rainfall (millimetres)**
31.2	1.8	39.1
8.1	12.4	22.7
32.4	0	1.3
0	0	0
1.3	9.7	32.4
22.78	15.5	8.1
39.1	5.0	31.2
24.9	10.7	24.9
23.5	21.3	23.5
114.2	29.0	114.2
11.7	1.8	21.1
31.5	0.2	27.9
52.4	44.7	7.2
1.0	4.8	1.0
27.9	15.5	52.4
16.2	7.2	0.2
21.1	0	1.0
10.4	25.0	0.5
0.5	11.0	0.3
0.1	16.0	29.0
0.7	107.2	42.5
11.4	22.7	21.3
1.4		20.3
0		

Table 3A Simulated annual rainfall data in the Lake Kariba District for the dry season (cont.)

Dry Season Rainfall (millimetres)	Dry Season Rainfall (millimetres)	Dry Season Rainfall (millimetres)
0	7.2	16.2
10.4	1.0	107.2
4.8	52.4	36.4
21.1	31.5	65.1
0	0.7	55.2
9.7	11.0	60.3
0.5	16.0	24.9
21.3	31.8	0
31.5	104.1	15.5
1.9	32.2	4.8
25.0	1.3	7.2
27.9	22.7	101.3
1.0	31.8	99.0
7.2	23.5	32.4
15.5	8.1	1.3
16.2	2.0	22.7
4.8	49.1	39.1
	52.3	52.4
	44.7	11.7
	70.1	

Source: Generated by Mini-Tab Software package (1985)

Table 4A Analysis of variance for actual and simulated rainfall data for the wet season in the Lake Kariba District

Group	Mean	N
1	710.471	34
2	820.762	34
GRAND MEAN	765.616	68

SOURCE	SUM OF SQUARES	D.F.	MEAN SQUARE	F RATIO	PROB.
BETWEEN	206790.441	1	206790.441	.553	.4598
WITHIN	24691029.911	66	374106.514		
TOTAL	24897820.352	67			

Table 5A Analysis of variance for actual and simulated rainfall data for dry season in the Lake Kariba District

Group	Mean	N
1	20.592	34
2	21.947	34
GRAND MEAN	21.265	68

SOURCE	SUM OF SQUARES	D.F.	MEAN SQUARE	F RATIO	PROB.
BETWEEN	31.661	1	31.661	.069	.7942
WITHIN	30460.034	66	461.516		
TOTAL	30491.695	67			

APPENDIX IV

LAKE KARIBA CATCHMENT AREA

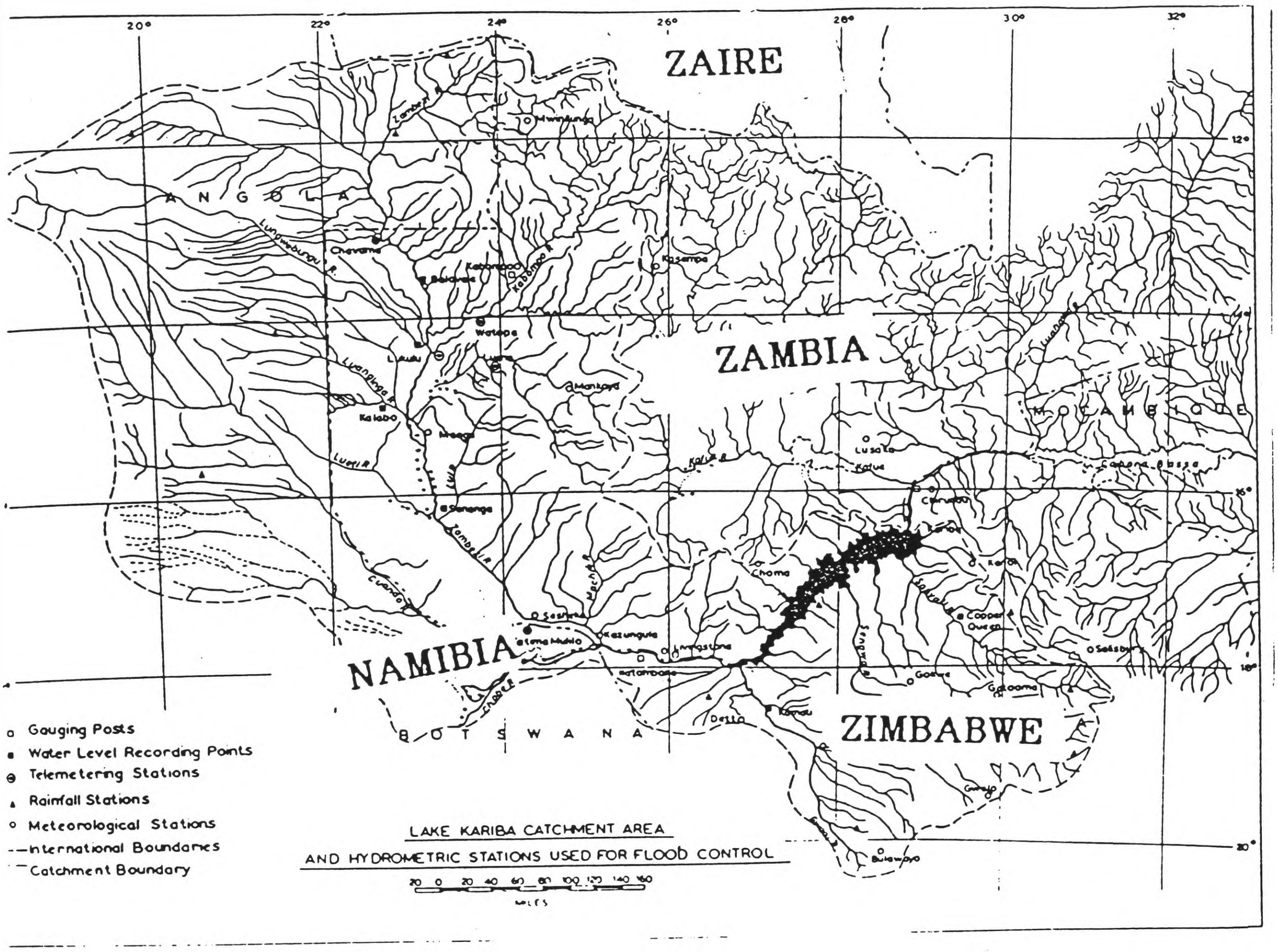


Figure 5A Lake Kariba Catchment Area

Source: Central African Power Corporation (CAPCO) 1986

APPENDIX V

GROSS MARGINS FOR THE DETERMINISTIC FRAMEWORK

Table 6A Estimated gross margin per hectare (ha) of maize at 1985 world prices*

Yield/ha		=	3,000 kg/ha
Price per kg adjusted for world prices		=	K0.38
Revenue/ha		=	K1,140.00
<u>Less variable costs:</u>			
Seed maize 20 kg/ha at K1.04/kg		=	K20.80
<u>Fertilizer</u>			
basal 250 kg at K0.60/kg		=	K150.00
top dressing 200 kg at K0.60/kg		=	K120.00
<u>Chemicals</u>			
DDT 10 kg at K9.30/kg		=	K93.00
labour and tractor hiring costs		=	<u>K181.20</u>
Total variable costs		=	K566.00
Gross margin	= K1,140 - K566	=	K574.00

***Note:** **Gross margins in this appendix are calculated on the basis of information from the Department of Agriculture and other experts.**

Table 7A Estimated gross margin per hectare (ha) of cotton at 1985 world prices

Yield/ha		=	1,000 kg
Price per kg adjusted for world prices		=	K0.40
Revenue/ha		=	K400.00
Less variable costs:			
Seed 20 kg/ha at K0.30/kg		=	K6.00
Chemicals			
DDT W.P 5 packs at K10/pack		=	K50.00
labour and tractor hiring costs		=	K50.00
Total variable costs		=	K106.00
Gross margin	= K400 - K106	=	K294.00

Table 8A Estimated gross margin per hectare (ha) of sunflower at 1985 world prices*

Yield/ha			=	850 kg
Price per kg adjusted for world prices			=	K0.83
Revenue/ha			=	K705.50
Less variable costs:				
Seed 8 kg/ha at K1.50/kg			=	K12.00
Fertilizer				
basal D compound 250 kg at K0.60/kg			=	K150.00
labour and tractor hiring costs			=	K62.00
Total variable costs			=	K224.00
Gross margin	=	K705.50 - K224	=	K481.50 or
				K482.00 approx.

Table 9A Estimated gross margin per hectare (ha) of sorghum at 1985 world prices

Yield/ha	=	1,300 kg/ha
Price per kg adjusted for world prices	=	K0.36
Revenue/ha	=	K468.00
<u>Less variable costs:</u>		
Seed 15 kg/ha at K0.85/kg	=	K12.75
<u>Fertilizer</u>		
basal X compound 100 kg/ha at K0.60/kg	=	K60.00
top dressing ammonia nitrate 100 kg/ha at K0.60/kg	=	K60.00
<u>Chemicals</u>		
DDT 75% W.P. 1kg/ha at K23.75/kg	=	<u>K23.75</u>
Total variable costs	=	K156.50
Gross margin = K468 - K156.50	=	K311.50 or
		K312.00 approx.

Table 10A Estimated gross margin per hectare (ha) of soyabeans at 1985 world prices

	Yield/ha	=	1,200 kg/ha
	Price per kg adjusted for world prices	=	K0.78
	Revenue/ha	=	K936.00
<u>Less variable costs:</u>			
	Seed 80 kg/ha at K1.90/kg	=	K152.00
<u>Fertilizer</u>			
	basal D compound 250 kg at K0.60/kg	=	K150.00
	top dressing urea 150 kg at K0.60/kg	=	K90.00
<u>Chemicals</u>			
	Treflan or lasso 2 litres at K10 each	=	K20.00
	labour and tractor hiring costs	=	<u>K174.00</u>
	Total variable costs	=	K586.00
	Gross margin = K936 - K586	=	K350.00

Table 11A Estimated gross margin per hectare (ha) of rice at 1985 world prices

	Yield/ha	=	1,000 kg/ha
	Price per kg adjusted for world prices	=	K1.07
	Revenue/ha	=	K1,070.00
Less variable costs:			
	Seed 60 kg/ha at K0.35/kg	=	K21.00
Fertilizer			
	basal D compound 200 kg at K0.60/kg	=	K120.00
	top dressing ammonia nitrate 200 kg at K0.60/kg	=	K60.00
	labour and tractor hiring costs	=	K308.00
	Total variable costs	=	K509.00
	Gross margin = K1,070 - K509	=	K561.00

Table 12A Estimated gross margin per hectare (ha) of wheat at 1985 world prices

Yield/ha	=	2,700 kg/ha
Price per kg adjusted for world prices	=	K0.44
Revenue/ha	=	K1,177.42
Less variable costs:		
Seed 90 kg/ha at K0.57/kg	=	K51.30
Fertilizer		
basal D compound 250 kg at K0.60/kg	=	K150.00
top dressing urea 150 kg/ha at K0.60/kg	=	K90.00
Chemicals		
primagram herbicides 20 kg/ha at K13.24/kg	=	K264.80
labour and tractor hiring costs	=	K268.00
Total variable costs	=	K824.10
Gross margin = K1,177.42 - K824.10	=	K353.32

APPENDIX VI

COST OF IRRIGATION FOR A HYPOTHETICAL 162,240 HECTARES OF LAND IN THE LAKE KARIBA DISTRICT

Table 13A Estimated cost of irrigation of a hypothetial 162,240 hectares of land in the Lake Kariba District at 1985 constant prices.

A - CAPTIAL COSTS

Capital Costs	World Bank calculated costs for a 350 ha at 2km pipe length K	This study's estimated costs for 162,240 ha to be irrigated for 27 km pipe length	Zone 1 13,260 ha 8.2%* K	Zone 2 32,340 ha 19.9%* K	Zone 3 49,860 ha 30.7%* K	Zone 4 30,180 ha 18.6%* K	Zone 5 36,600 ha 22.6%* K	Total hectarage to be irrigated 162,240ha K
1. Civil works	30,000	civil works	2,000	6,000	9,000	6,000	7,000	30,000
2. 2 diesel motor pumps capacity (140KW)	140,000	diesel pumps capacity 6160KW	505,000	1,226,000	1,891,000	1,146,000	1,392,000	6,160,000
3. Main rising pipe ϕ 500mm and 2 km long	240,000	4 pipes ϕ 500 mm each and 27 km long	17,004,000	41,265,000	63,660,000	38,569,000	46,863,000	207,361,000
4. Water reservior capacity 4000m^3	200,000	Water reserviour capacity 4,000m^3 x 44 or 176,000m^3	722,000	1,715,000	2,702,000	1,637,000	1,989,000	8,801,000
5. Irrigation network, main lined canals and unlined tertiary canals at K800/ha	280,000	Irrigation network main lined canals and and unlined tertiary canals at K800/ha	10,513,000	25,829,000	39,846,000	24,141,000	29,333,000	129,662,000
SUB TOTALS	890,000		28,746,000	70,077,000	108,108,000	65,499,000	79,584,000	352,014,000
6. Contingency 15%	134,000		4,312,000	10,512,000	16,216,000	9,825,000	11,938,000	52,800,000
GRAND TOTALS	1,024,000		33,058,000	80,589,000	124,324,000	75,324,000	91,522,000	404,814,000
Cost per hectare undiscounted	K2926/ha		K2493/ha	K2492/ha	K2493/ha	K2496/ha	K2501/ha	K2495/ha
Discounting at 5% interest on annuity for 50 years	None		K137/ha	K137/ha	K137/ha	K137/ha	K137/ha	K137/ha

Note: * represent the contribution of land of each zone to the total land area of 162,240 hectares. Hence cost of irrigation is apportioned accordingly.

Table 13A **Estimated cost of irrigation of a hypothetial 162,240 hectares of land in the Lake Kariba District at 1985 constant prices.**

B - OPERATION AND MAINTENANCE COSTS (O & M)

O & M costs per item	World Bank calculated O & M costs on a 350 ha and 2km pipe line K	This study's estimated costs on a 162,240 ha and a 27 km pipe line	Zone 1 13,260 ha 8.2% K	Zone 2 32,340 ha 19.9% K	Zone 3 49,860 ha 30.7% K	Zone 4 30,180 ha 18.6% K	Zone 5 36,600 ha 22.6% K	Total hectarage to be irrigated 162,240ha K
Civil works	9,400	civil works	800	1,900	2,900	1,700	2,100	9,400
Pumps	14,000	pumps	850,000	2,063,000	3,183,000	1,928,000	2,343,000	10,367,000
Irrigation Network	14,000	Irrigation Network	43,000	105,000	161,000	98,000	119,000	526,000
Fuel costs at K0.25/Kwh	134,250	Fuel costs at K0.25/Kwh	277,000	673,000	1,038,000	629,000	764,000	3,381,000
Total O & M costs	171,650		1,557,800	2,842,900	4,384,900	2,556,700	3,228,100	14,283,400
Undiscounted costs per ha	K490/ha		K117/ha	K88/ha	K52/ha	K46/ha	K88/ha	K88/ha
Discounted O& M costs at 5% interest annuity for 50 years	$\frac{490}{18.256}$ = K27/ha	18.256	K6/ha	K5/ha	K3/ha	K3/ha	K5/ha	K5/ha

Table 13A **Estimated cost of irrigation of a hypothetial 162,240 hectares of land in the Lake Kariba District at 1985 constant prices.**

C - CAPITAL, OPERATION AND MAINTENANCE COSTS PER HECTARE MILLIMETRE OF WATER

Costs	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Capital costs/ha	K137	K137	K137	K137	K137
O & M costs/ha	K6	K5	K3	K3	K5
Total costs/ha	K143	K142	K140	K140	K142
Cost per ha/mm of water	$\frac{143}{1000}$	$\frac{142}{1000}$	$\frac{140}{1000}$	$\frac{149}{1000}$	$\frac{142}{1000}$
	K0.143	K0.142	K0.140	K0.140	K0.142

Source: **World Bank, 1983 and discussions with several experts during field survey in 1986.**

APPENDIX VII

LAKE KARIBA WATER LEVELS ON MONTHLY BASIS

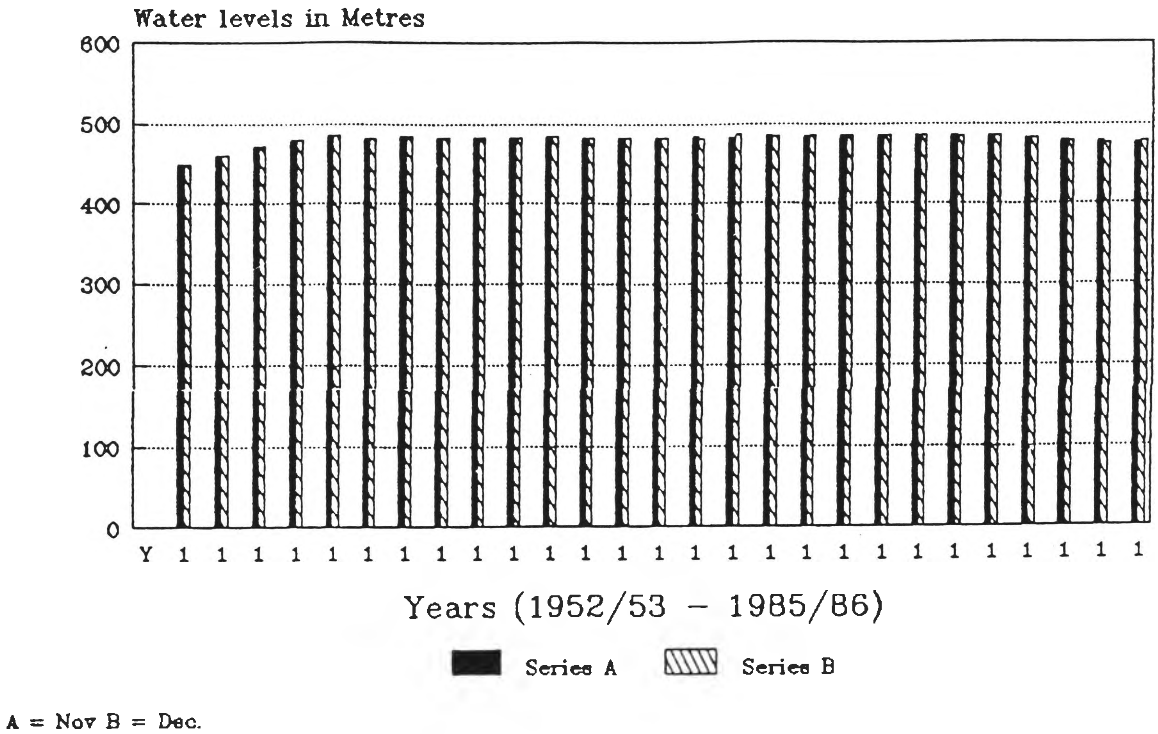


Figure 6A Lake Kariba water levels November - December 1959/60 to 1985/86

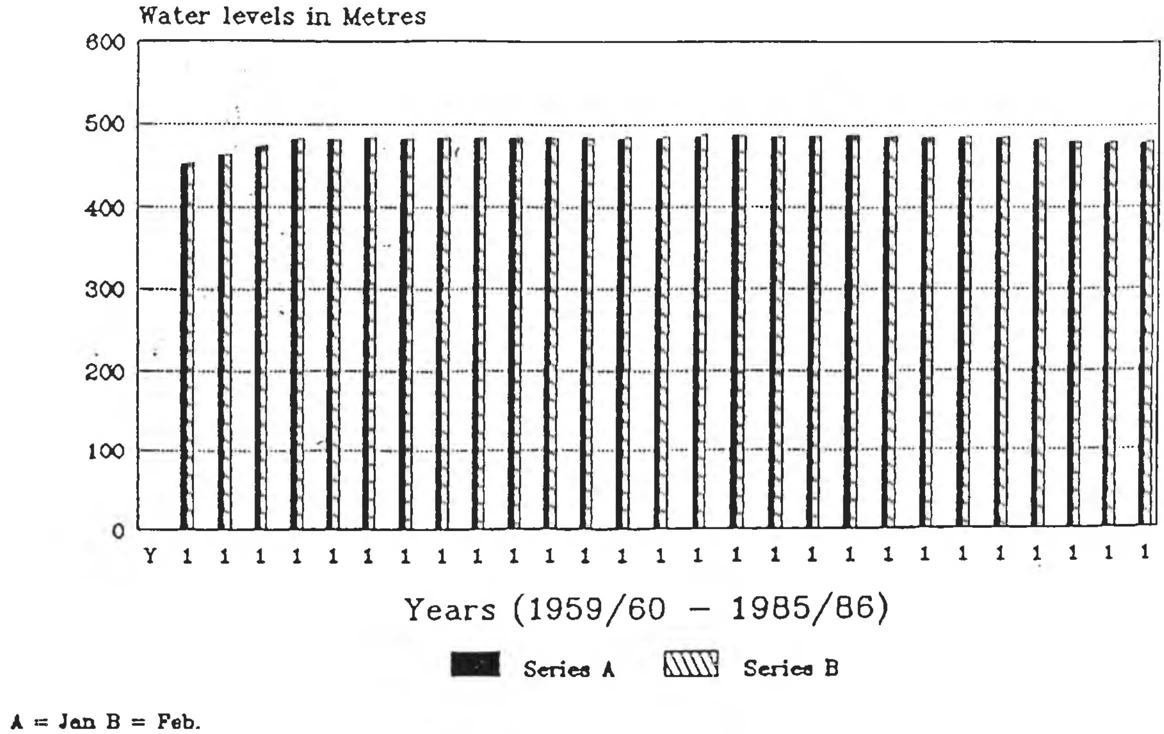


Figure 7A Lake Kariba water levels January - February 1959/60 to 1985/86

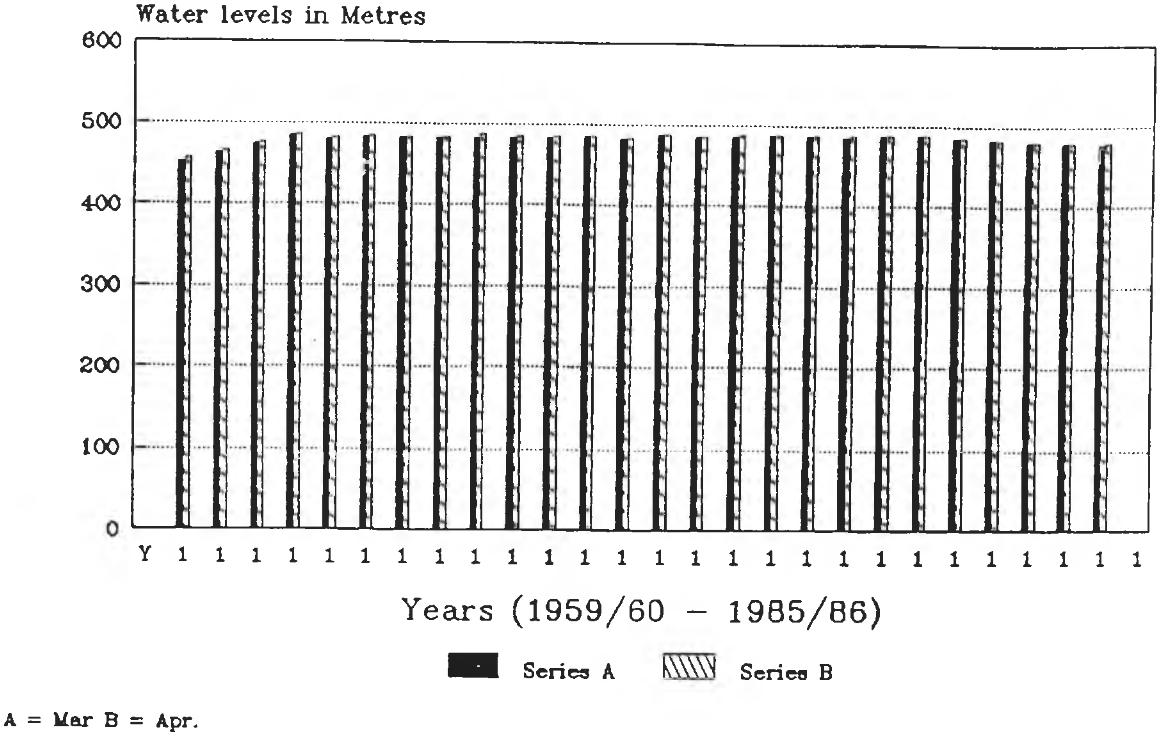


Figure 8A Lake Kariba water levels March - April 1959/60 to 1985/86

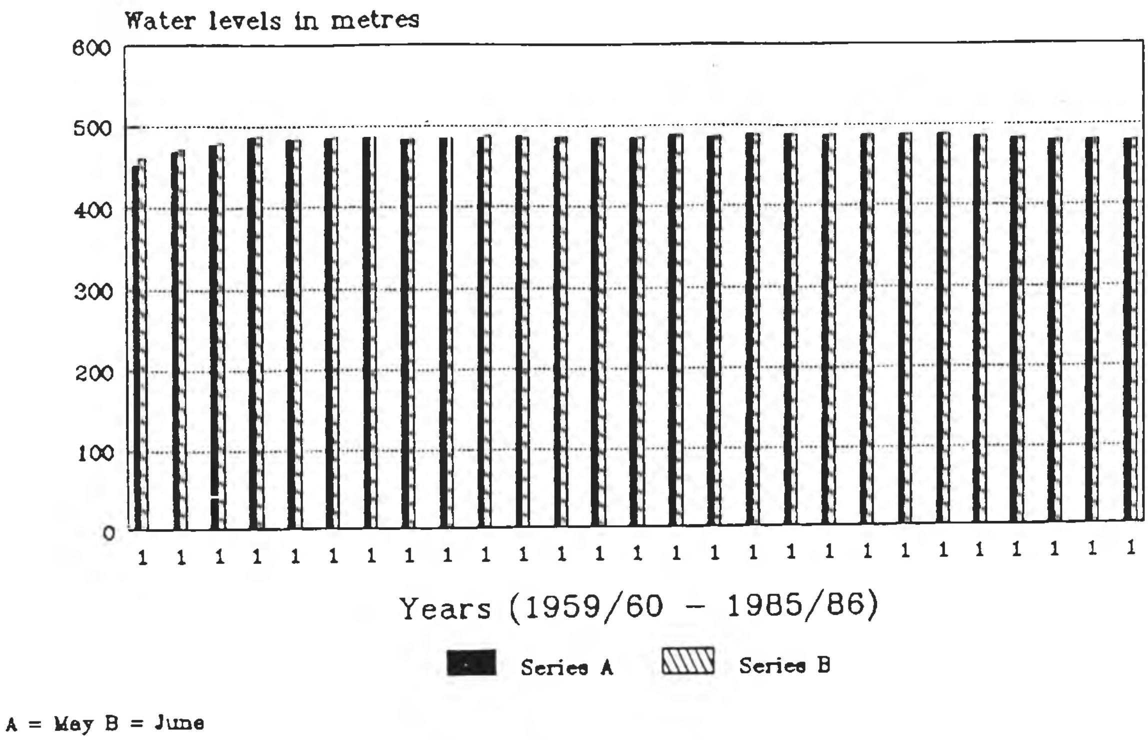


Figure 9A Lake Kariba water levels May - June 1959/60 to 1985/86

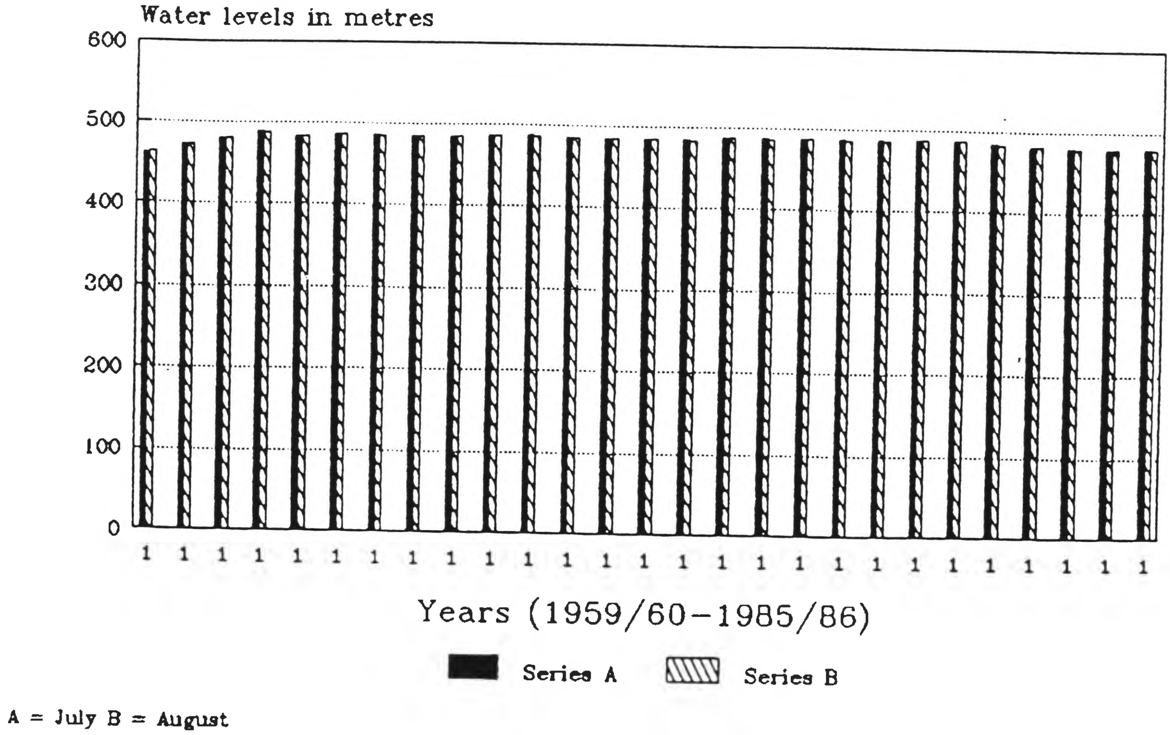


Figure 10A Lake Kariba water levels July - August 1959/60 to 1985/86

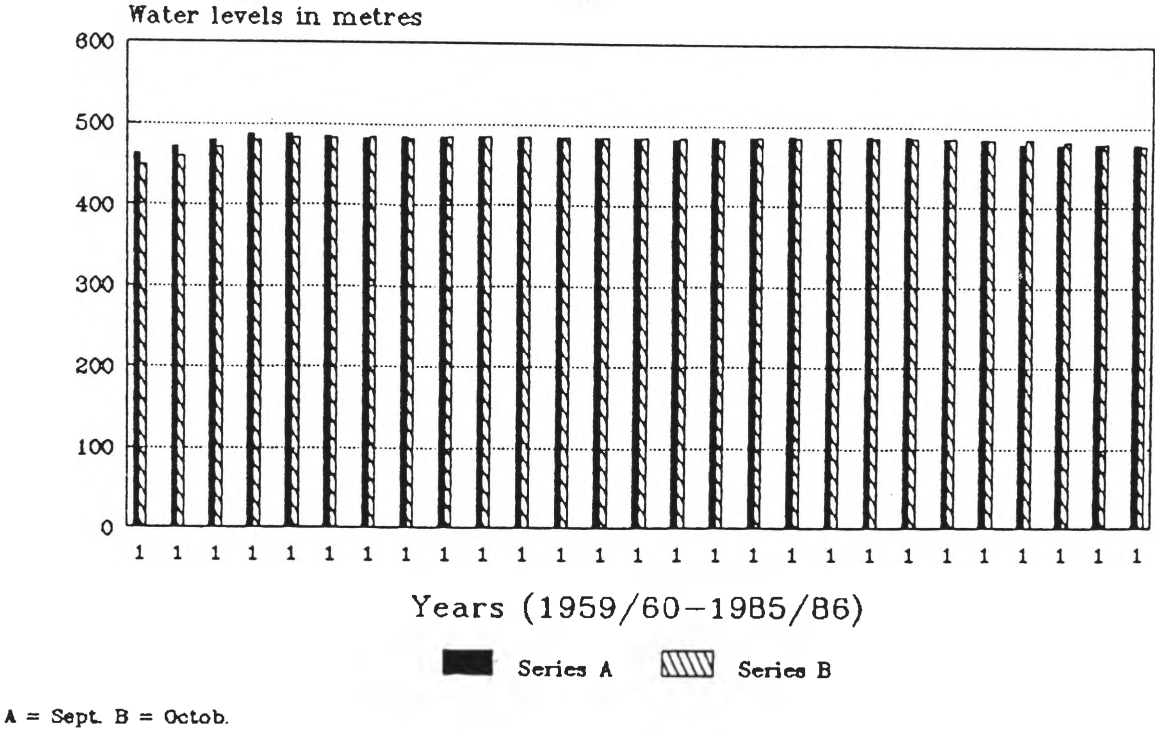


Figure 11A Lake Kariba water levels September - October 1959/60 to 1985/86

APPENDIX VIII

SUBJECTIVELY ESTIMATED EXPECTED GROSS MARGINS FOR THE STOCHASTIC FRAMEWORK

Table 14A Frequency distribution for actual rainfall in the Lake Kariba District 1952/53 to 1985/86

Class Interval	Frequency	Probability Levels	Cumulative Frequency
$350 \leq 450$	3	0.09	0.09
$450 \leq 550$	4	0.12	0.21
$550 \leq 650$	7	0.20	0.41
$650 \leq 750$	8	0.23	0.64
$750 \leq 850$	3	0.09	0.73
$850 \leq 950$	4	0.12	0.85
$950 \leq 1050$	2	0.06	0.91
$1050 \leq 1150$	1	0.03	0.94
$1150 \leq 1250$	2	0.06	1.00

Table 15A **Expected gross margins and deviations for selected scenarios**

Scenario 1

Year	State of Nature (Rainfall) mm	P_{ik} Probability of State of Nature percent	MAIZE G_{ijk} Kwacha	MAIZE $P_{ik}G_{ijk}$ Kwacha	MAIZE Y_{ik} Kwacha	COTTON G_{ijk} Kwacha	COTTON $P_{ik}G_{ijk}$ Kwacha	COTTON Y_{ik} Kwach
1	675	0.23	250	58	63	250	58	68
2	495	0.12	100	12	-87	150	18	-32
3	405	0.09	50	5	-137	100	9	-82
4	1035	0.06	300	36	113	250	15	68
5	855	0.12	300	36	113	200	24	18
6	675	0.23	250	58	63	250	58	68
Total			---	**187**		---	**182**	

Note: $Y_{ik} = G_{ijk} - \Sigma(P_{ik})(G_{ijk})$

Table 16A Expected gross margins and deviations for selected scenarios

Scenario 1

Year	State of Nature (Rainfall) mm	P_{ik} Probability of State of Nature percent	SUNFLOWER G_{ijk} Kwacha	SUNFLOWER $P_{ik}G_{ijk}$ Kwacha	SUNFLOWER Y_{ik} Kwacha	SORGHUM G_{ijk} Kwacha	SORGHUM $P_{ik}G_{ijk}$ Kwacha	SORGHUM Y_{ik} Kwach
1	675	0.23	200	46	58	300	69	124
2	495	0.12	50	6	-92	150	18	-26
3	405	0.09	20	2	-122	150	14	-26
4	1035	0.06	300	18	158	200	12	24
5	855	0.12	200	24	18	200	24	24
6	675	0.23	200	46	18	300	69	124
Total			---	**142**		---	**176**	

Table 17A Expected gross margins and deviations for selected scenarios

Scenario 1

Year	State of Nature (Rainfall) mm	P_{ik} Probability of State of Nature percent	SOYABEANS G_{ijk} Kwacha	$P_{ik}G_{ijk}$ Kwacha	Y_{ik} Kwacha	RICE G_{ijk} Kwacha	$P_{ik}G_{ijk}$ Kwacha	Y_{ik} Kwach
1	675	0.23	150	35	23	0	0	-54
2	495	0.12	0	0	-127	0	0	-54
3	405	0.09	0	0	-127	0	0	-54
4	1035	0.06	350	21	223	500	30	446
5	855	0.12	300	36	173	200	24	146
6	675	0.23	150	35	23	0	0	-54
Total			---	**127**		---	**54**	

Table 18A Expected gross margins and deviations for selected scenarios

Scenario 1

Year	State of Nature (Rainfall) mm	P_{ik} Probability of State of Nature percent	WHEAT G_{ijk} Kwacha	$P_{ik}G_{ijk}$ Kwacha	Y_{ik} Kwacha
1	675	0.23	0	0	-84
2	495	0.12	0	0	-84
3	405	0.09	0	0	-84
4	1035	0.06	300	18	216
5	855	0.12	200	24	116
6	675	0.23	0	42	-84
Total			---	84	

Table 19A Expected gross margins and deviations for selected scenarios

Scenario 2

Year	State of Nature (Rainfall) mm	P_{ik} Probability of State of Nature percent	MAIZE G_{ijk} Kwacha	MAIZE $P_{ik}G_{ijk}$ Kwacha	MAIZE Y_{ik} Kwacha	COTTON G_{ijk} Kwacha	COTTON $P_{ik}G_{ijk}$ Kwacha	COTTON Y_{ik} Kwach
1	585	0.20	150	30	27	200	40	59
2	495	0.12	100	12	-23	150	6	9
3	765	0.09	250	23	147	250	23	109
4	405	0.20	50	5	-73	100	9	-41
5	585	0.20	150	30	27	200	40	59
6	765	0.09	250	23	147	250	23	109
Total			---	**123**		---	**141**	

Note: $Y_{ik} = G_{ijk} - \Sigma(P_{ik})(G_{ijk})$

Table 20A Expected gross margins and deviations for selected scenarios

Scenario 2

Year	State of Nature (Rainfall) mm	P_{ik} Probability of State of Nature percent	SUNFLOWER G_{ijk} Kwacha	SUNFLOWER $P_{ik}G_{ijk}$ Kwacha	SUNFLOWER Y_{ik} Kwacha	SORGHUM G_{ijk} Kwacha	SORGHUM $P_{ik}G_{ijk}$ Kwacha	SORGHUM Y_{ik} Kwach
1	585	0.20	100	20	-84	250	50	82
2	495	0.12	50	6	-34	150	18	-18
3	765	0.09	200	18	116	200	18	32
4	405	0.20	20	2	-64	150	14	-18
5	585	0.20	100	20	16	250	50	82
6	765	0.09	200	18	116	200	18	32
Total			---	**84**		---	**168**	

Table 21A Expected gross margins and deviations for selected scenarios

Scenario 2

Year	State of Nature (Rainfall) mm	P_{ik} Probability of State of Nature percent	SOYABEANS G_{ijk} Kwacha	SOYABEANS $P_{ik}G_{ijk}$ Kwacha	SOYABEANS Y_{ik} Kwacha	RICE G_{ijk} Kwacha	RICE $P_{ik}G_{ijk}$ Kwacha	RICE Y_{ik} Kwach
1	585	0.20	100	20	42	40	8	12
2	495	0.12	30	4	-28	30	4	2
3	765	0.09	70	6	12	60	5	32
4	405	0.09	20	2	-38	20	2	-8
5	585	0.20	100	20	42	20	4	-8
6	765	0.09	70	6	12	60	5	32
Total			---	**58**		---	**28**	

Table 22A Expected gross margins and deviations for selected scenarios

Scenario 2

Year	State of Nature (Rainfall) mm	P_{ik} Probability of State of Nature percent	WHEAT G_{ijk} Kwacha	$P_{ik}G_{ijk}$ Kwacha	Y_{ik} Kwacha
1	585	0.20	40	8	7
2	495	0.12	30	4	-3
3	765	0.09	60	5	27
4	405	0.09	30	3	-3
5	585	0.20	40	8	7
6	765	0.09	60	5	27
Total			---	**33**	

Table 23A Expected gross margins and deviations for selected scenarios

Scenario 3

Year	State of Nature (Rainfall) mm	P_{ik} Probability of State of Nature percent	MAIZE G_{ijk} Kwacha	MAIZE $P_{ik}G_{ijk}$ Kwacha	MAIZE Y_{ik} Kwacha	COTTON G_{ijk} Kwacha	COTTON $P_{ik}G_{ijk}$ Kwacha	COTTON Y_{ik} Kwach
1	945	0.12	400	48	211	150	18	-30
2	405	0.09	50	5	-139	100	9	-80
3	1035	0.06	300	18	111	250	15	70
4	585	0.20	150	30	-39	200	40	20
5	675	0.23	250	58	61	250	58	70
6	585	0.23	150	30	-39	200	40	20
Total			---	**189**		---	**180**	

Note: $Y_{ik} = G_{ijk} - \Sigma(P_{ik})(G_{ijk})$

Table 24A **Expected gross margins and deviations for selected scenarios**

Scenario 3

Year	State of Nature (Rainfall) mm	P_{ik} Probability of State of Nature percent	SUNFLOWER G_{ijk} Kwacha	SUNFLOWER $P_{ik}G_{ijk}$ Kwacha	SUNFLOWER Y_{ik} Kwacha	SORGHUM G_{ijk} Kwacha	SORGHUM $P_{ik}G_{ijk}$ Kwacha	SORGHUM Y_{ik} Kwach
1	945	0.12	200	24	70	150	18	-63
2	405	0.09	20	2	-110	150	14	-63
3	1035	0.06	300	18	170	200	12	-13
4	585	0.20	100	20	-30	250	50	37
5	675	0.23	200	46	70	300	69	87
6	585	0.20	100	20	-30	250	50	37
Total			---	**130**		---	**213**	

Table 25A Expected gross margins and deviations for selected scenarios

Scenario 3

Year	State of Nature (Rainfall) mm	P_{ik} Probability of State of Nature percent	SOYABEANS G_{ijk} Kwacha	$P_{ik}G_{ijk}$ Kwacha	Y_{ik} Kwacha	RICE G_{ijk} Kwacha	$P_{ik}G_{ijk}$ Kwacha	Y_{ik} Kwach
1	945	0.12	300	364	157	450	54	351
2	405	0.09	20	2	-123	20	2	-79
3	1035	0.06	350	30	207	500	30	401
4	585	0.20	100	20	-43	20	4	-79
5	675	0.23	150	35	7	20	5	-79
6	585	0.20	100	20	-43	20	4	-79
Total			---	**143**		---	**99**	

Table 26A Expected gross margins and deviations for selected scenarios

Scenario 3

Year	State of Nature (Rainfall) mm	P_{ik} Probability of State of Nature percent	WHEAT G_{ijk} Kwacha	$P_{ik}G_{ijk}$ Kwacha	Y_{ik} Kwacha
1	945	0.12	450	54	347
2	405	0.09	30	3	-73
3	1035	0.06	300	18	197
4	585	0.20	40	8	-63
5	675	0.23	50	12	-53
6	585	0-.20	40	8	-63
Total			---	**103**	

APPENDIX IX

A SIMPLIFIED EMPIRICAL SPECIFICATION OF TARGET MOTAD MODEL

Table 27A A simplified Target MOTAD model for the "with irrigation" framework using data from scenario 1[a]

Maximize expected gross margin =

$$187X_{111} + 182X_{112} + 142X_{113} + 176X_{114} + 127X_{115} + 54X_{116} + 42X_{117} - 0.05B_{111} - 0.05B_{112} - 0.05B_{113} - 0.05B_{114} - 0.05B_{115} - 0.05B_{116} - 0.05B_{117} - 0.142W_{111} - 0.142W_{112} - 0.142W_{113} - 0.142W_{114} - 0.142W_{115} - 0.142W_{116} - 0.142W_{117} \quad (1)$$

Subject to:

$$X_{111} + X_{112} + X_{113} + X_{114} + X_{115} + X_{116} + X_{117} \leq 13{,}260 \quad (2)$$

$$22X_{111} + 42X_{112} + 15X_{113} + 37X_{114} + 16X_{115} + 33X_{116} + 18X_{117} \leq 2{,}000{,}000 \quad (3)$$

$$36X_{111} + 20X_{112} + 10X_{113} + 8X_{114} + 25X_{115} + 14X_{116} + 30X_{117} - 1B_{111} - 1B_{112} - 1B_{113} - 1B_{114} - 1B_{115} - 1B_{116} - 1B_{117} \leq 3{,}000{,}000 \quad (4)$$

$$229X_{111} + 79X_{112} + 690X_{113} + 11X_{114} + 740X_{115} + 990X_{116} + 890X_{117} - 1W_{111} - W_{112} - 1W_{113} - 1W_{114} - 1W_{115} - 1W_{116} - 1W_{117} \leq 0 \quad (5)$$

$$1W_{111} - 1W_{112} + 1W_{113} + 1W_{114} + 1W_{115} + 1W_{116} + 1W_{117} \leq 887{,}038{,}600 \quad (6)$$

$$63X_{111} + 68X_{112} + 58X_{113} + 124_{114} + 23X_{115} - 54X_{116} - 84X_{117} + Y_1 \geq 100{,}000{,}000 \quad (7)$$

$$-87X_{111} - 32X_{112} - 92X_{113} - 26X_{114} - 127X_{115} - 54X_{116} - 84X_{117} + Y_2 \geq 100{,}000{,}000 \quad (8)$$

$$137X_{111} - 82X_{112} - 122X_{113} - 26X_{114} - 127X_{115} - 54X_{116} - 84X_{117} + Y_3 \geq 100{,}000{,}000 \quad (9)$$

$$113X_{111} + 68X_{112} + 158X_{113} + 24X_{114} + 223X_{115} + 446X_{116} + 216X_{117} + Y_4 \geq 100{,}000{,}000 \quad (10)$$

$$113X_{111} + 18X_{112} + 158X_{113} + 24X_{114} + 173X_{115} + 146X_{116} + 116X_{117} + Y_5 \geq 100{,}000{,}000 \quad (11)$$

$$63X_{111} + 68X_{112} + 18X_{113} + 124X_{114} + 23X_{115} - 554X_{116} - 84X_{117} + Y_6 \geq 100{,}000{,}000 \quad (12)$$

$$0.23Y_1 + 0.12Y_2 + 0.09Y_3 + 0.06Y_4 + 0.12Y_5 + 0.23Y_6 \leq 20{,}000{,}000 \quad (13)$$

(a) only data for season 1, zone 1 and scenario 1 is considered in the above model.

Where:

(a) an objective function is in (1)

(b) the constraints of land, labour, capital, soil moisture and irrigation water are represented in (2) to (6) respectively

(c) constraints (7) to (12) represent deviations from target gross margins

(d) the 100,000,000 on the right hand side of (7) to (12) is measured in Kwacha and represent the regional target gross margin of K100 million

(e) the probabilities assocated with the various states of nature are in (13)

(f) the 20,000,000 on the right hand side of (13) is measured in Kwachas and represent the risk parameter of K20 million

(g) other variables in the model were defined in Chapter 4.